Dynamic Timber

A Seismic Analysis Workflow for Tall Timber Structures with Variable Parameters

Annebel van der Meulen | 6031579 | TU Delft - Building Technology Thesis | P5 presentation

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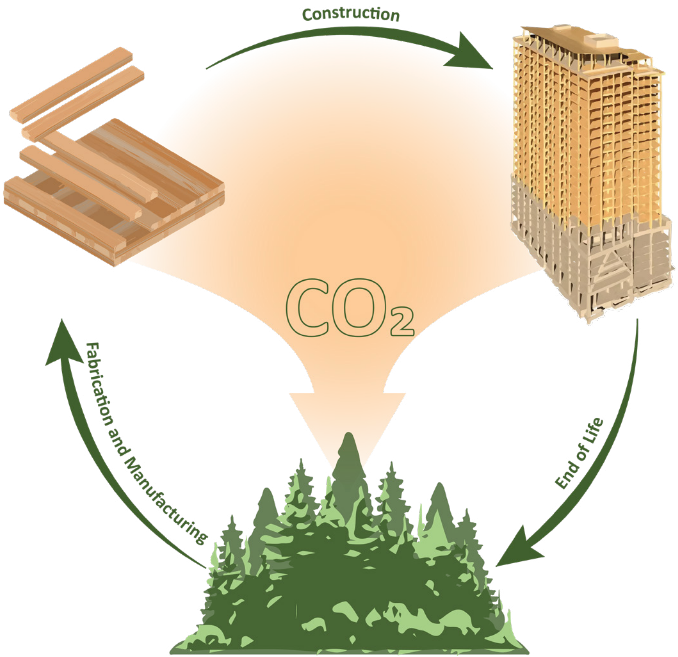
Background

Why Timber?

Carbon Neutral

- Carbon sequestration
- 1m^3 of wood = 1.1 tons of CO_2



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Occupant Health

- Natural materials make for healthier spaces

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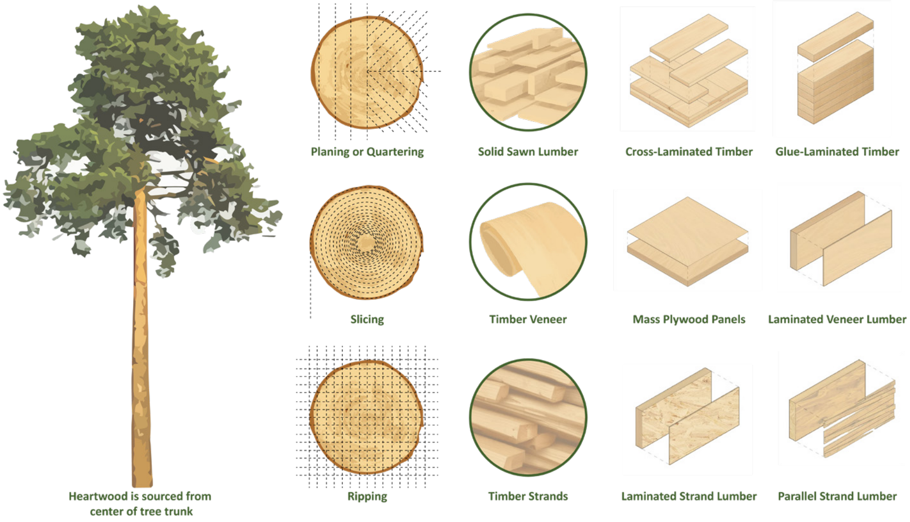

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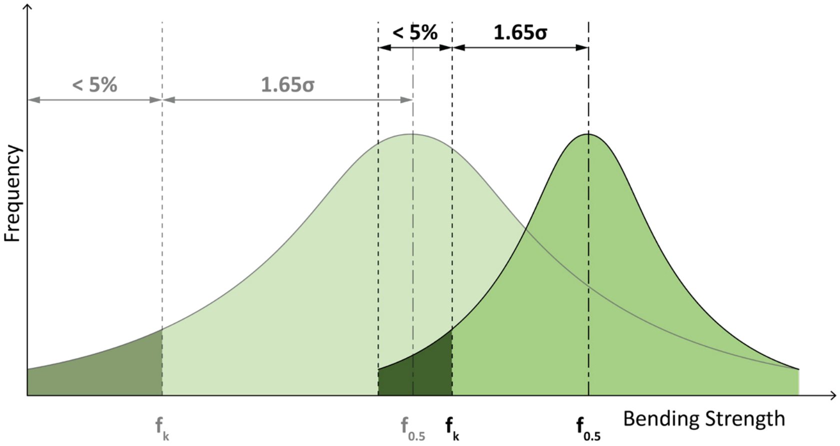

f_k = Characteristic Strength

$f_{0.5}$ = Mean Strength

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Occupant Health

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New Engineered Products

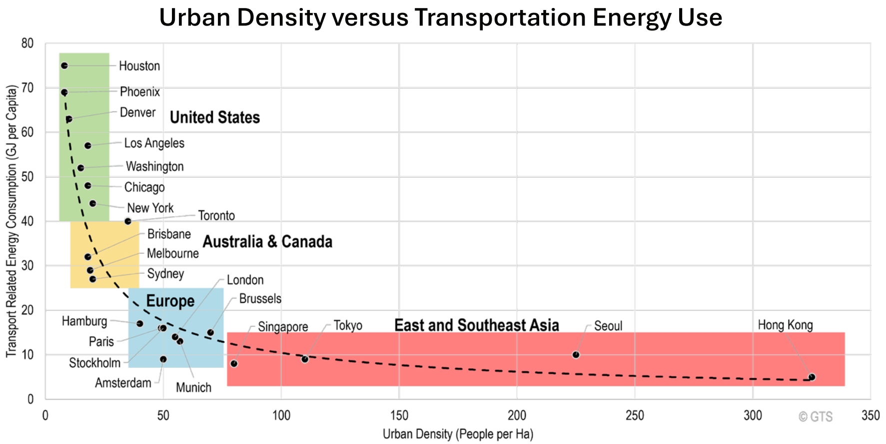
- Elements are more reliable
- New structure types possible

Mjøstårnet - Brumunddal, Norway - Voll Arkitekter

Why Tall Timber?

Increased Density

- Higher density cities use less transportation energy

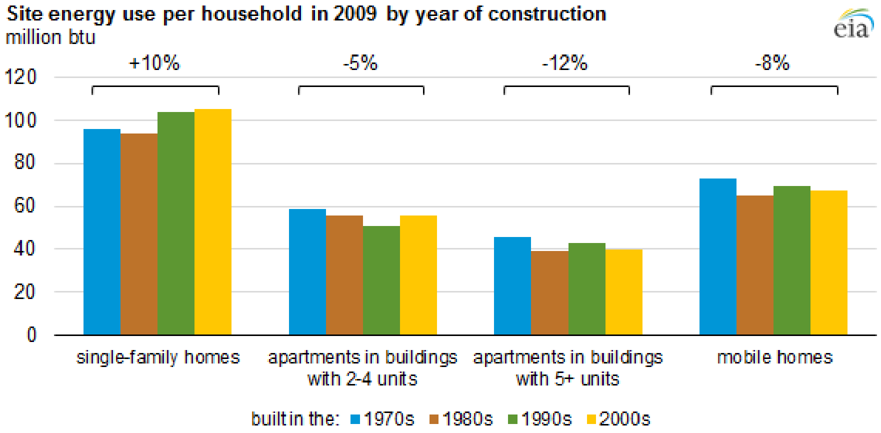


Source: The Geography of Transportation Systems

Why Tall Timber?

Increased Density

- Higher density cities use less transportation energy
- High density living has lower emissions per floor area



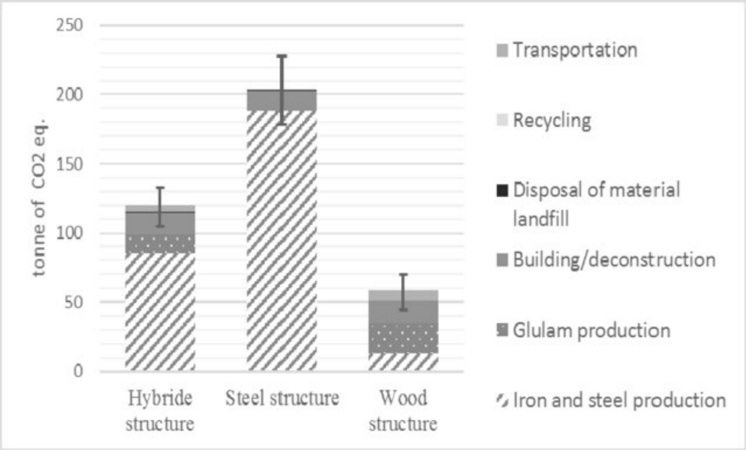
Source: US Energy Information Administration

Why Tall Timber?

Increased Density

- Higher density cities use less transportation energy
- High density living has lower emissions per floor area
- Need low carbon solutions for such structures

Material carbon footprint comparison for like structures



Source: Laurent et al. 2019

Why Tall Timber?

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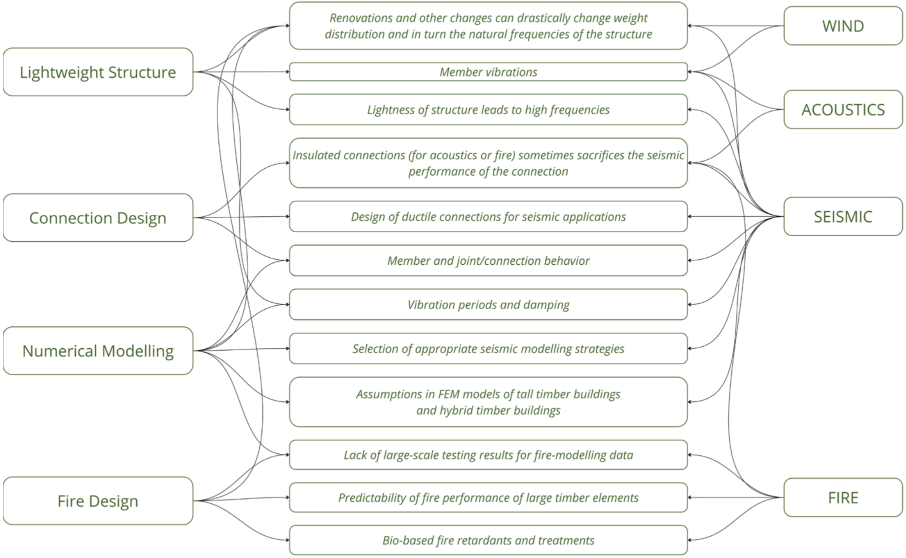
Current Challenges

- Lightweight structure
- Connection design
- Computational modelling
- Fire design

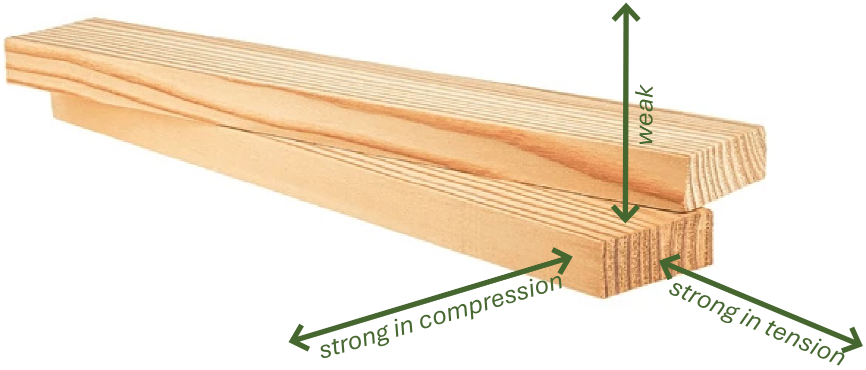


Why Seismic Analysis?

(of tall timber structures)

Material Challanges

- Anisotropic material
    - behaves differently in each direction



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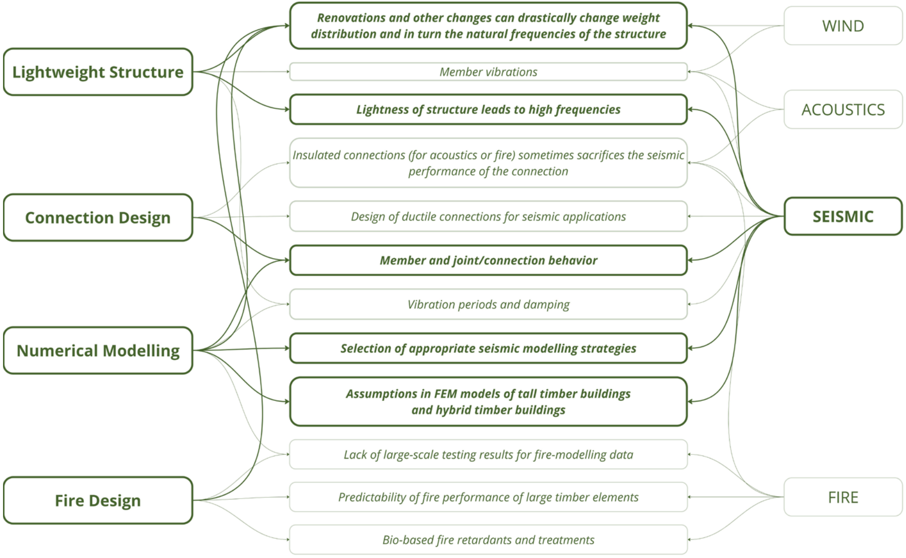
Tall Structure Challenges

- Relatively lightweight
- Properties can change through the structure's lifetime



Why Seismic Analysis Workflow?

(of tall timber structures)

Current Modelling Strategies

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- Complex to implement
  - More accurate models are time-consuming for practice

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Current Modelling Strategies

- Complex to implement
  - More accurate models are time-consuming for practice
- Disconnected from the main design workflow
- Does not consider changing parameters overtime

Research Goals

Problem Statement

Current **practice-oriented seismic analysis** methods for *tall timber structures* are **isolated** from the main design process, **complex to implement**, and do not consider **variability of parameters** over the structure's lifetime.

Objective

How will this problem be addressed by the research project?

Develop a **practice-oriented seismic analysis** workflow for *tall timber structures* which is **integrated** into the main design process, is **quick** and **adaptable** to implement, and includes **lifetime analysis** options.

Questions

What is the existing practice and knowledge for the seismic analysis of tall timber structures?

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How can a lifetime analysis be incorporated into the workflow?

What is the accuracy, applicability, and advantage of this workflow?

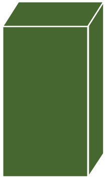
What is the impact of the lifetime analysis?

How does the workflow impact the decision making process for the engineer?

Project Scope

Project Scope

Form and Function



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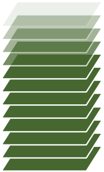
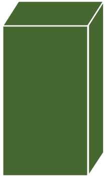


8+ stories

Residential

Project Scope

Form and Function



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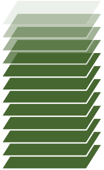
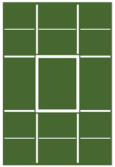


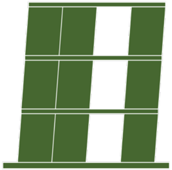
8+ stories

Residential

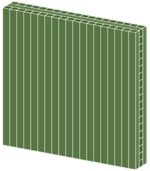
Structural System



Central Core



Shear Walls



CLT Walls

Project Scope

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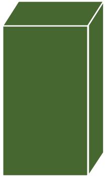

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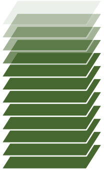


8+ stories

Residential

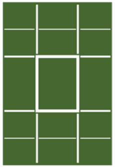
Building Standard

Europe Region

EN 1995

EN 1998

Structural System



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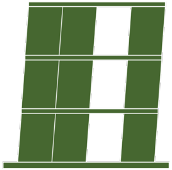

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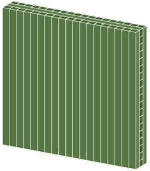

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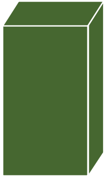
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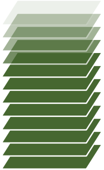
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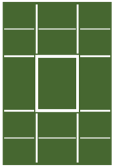
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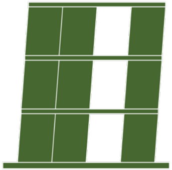
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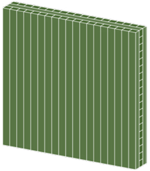
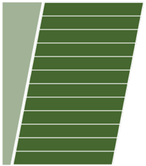

CLT Walls

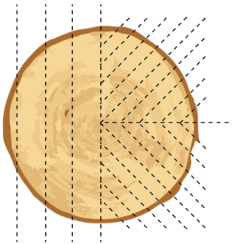
Analysis


Static Linear Analysis


Post Event

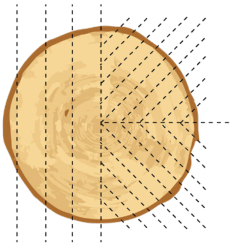

Over Time

Cross Laminated Timber (CLT)



Planing or Quartering

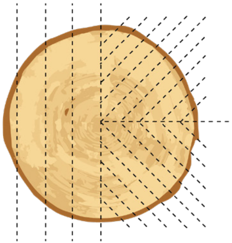
Cross Laminated Timber (CLT)



Planing or Quartering

Solid Sawn Lumber

Cross Laminated Timber (CLT)



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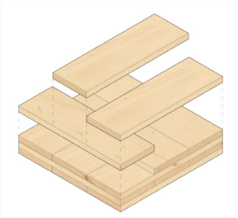

Cross-Laminated Timber

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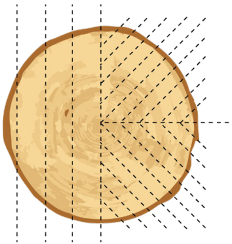

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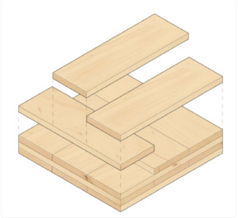

Cross-Laminated Timber

CLT Wall Construction

CLT Panels

- Single- or

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- Single- or multi-panel

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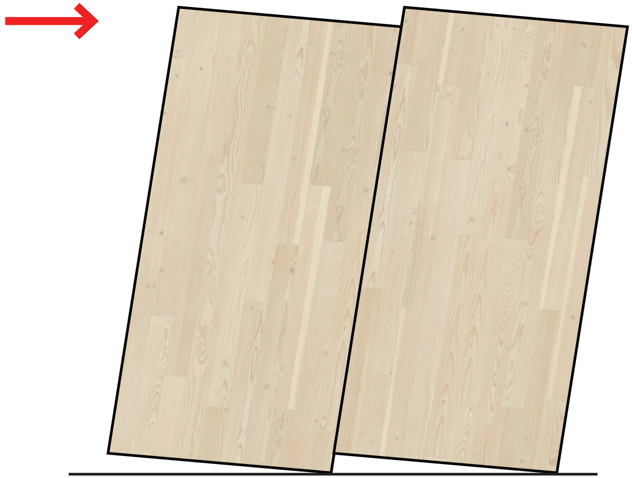
- Single- or multi-panel
  - Work together to resist lateral loads



CLT Wall Construction

CLT Panels

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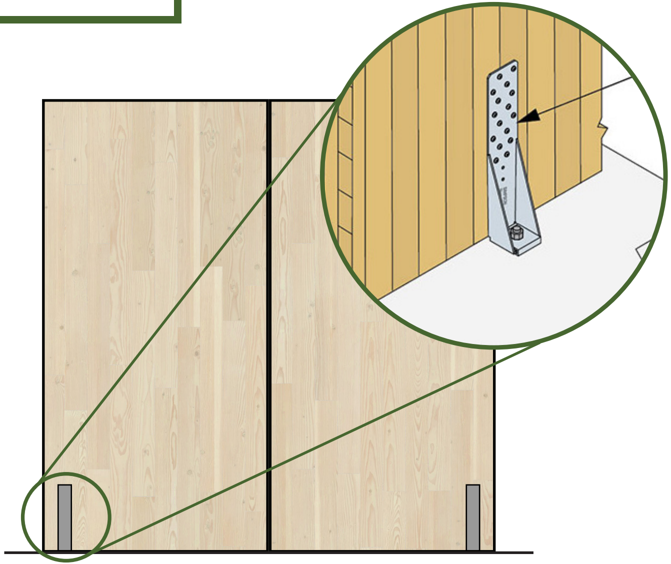
Hold downs



CLT Wall Construction

CLT Panels

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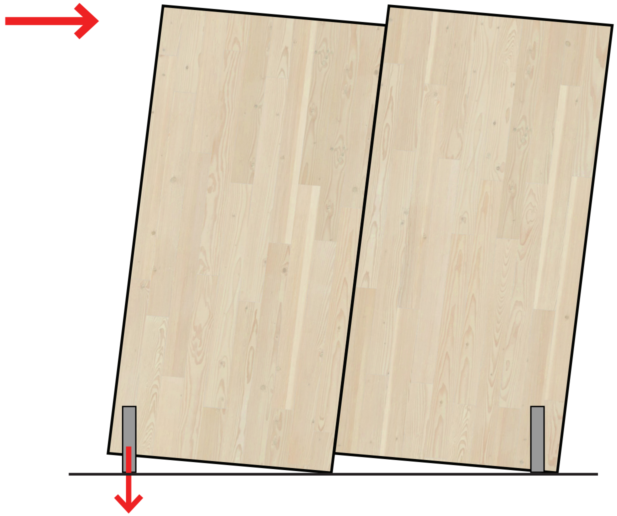
Hold downs

- Resist tension from overturning



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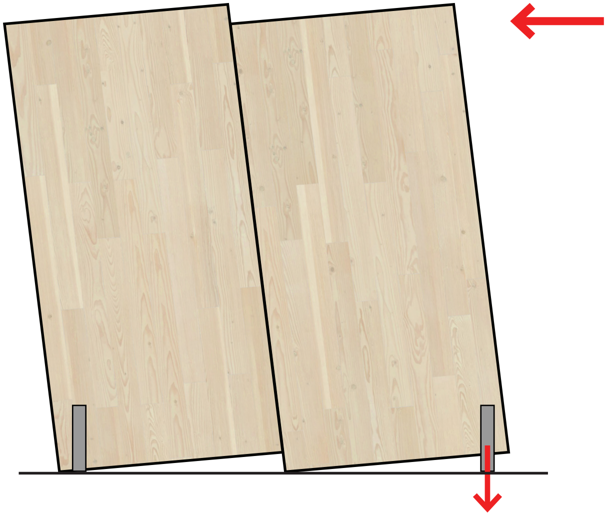

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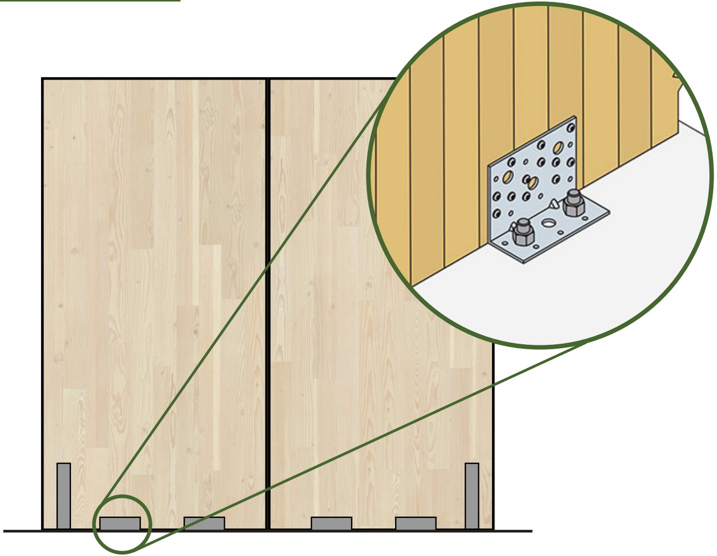
Angle brackets



CLT Wall Construction

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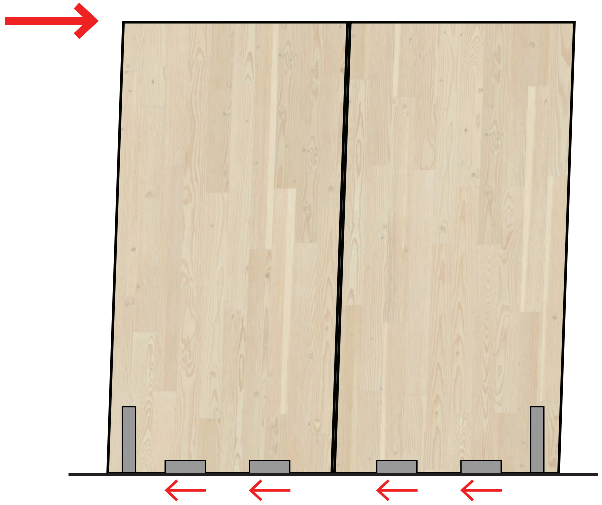
- Resist shear forces at base



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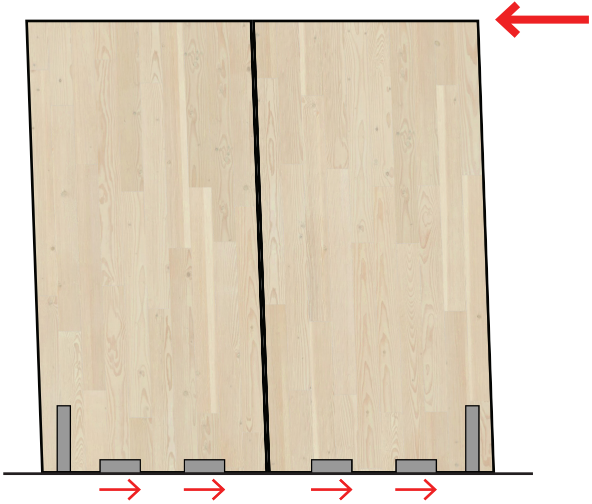

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Angle brackets

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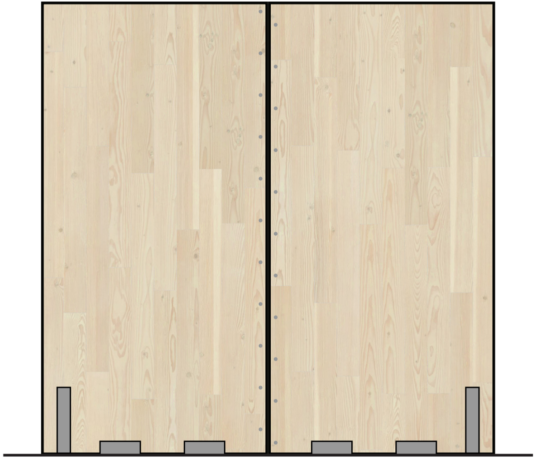
Screws in joint



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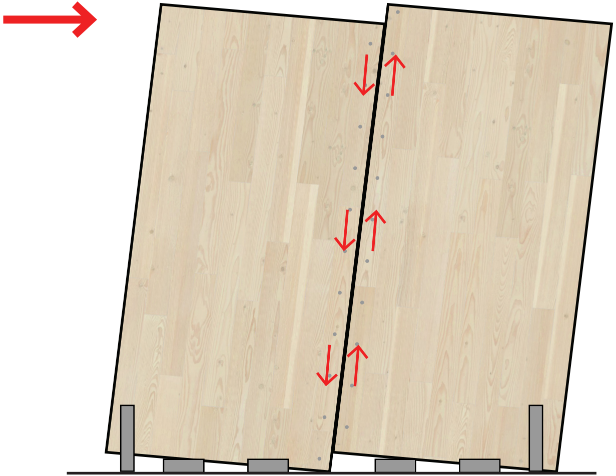
Angle brackets

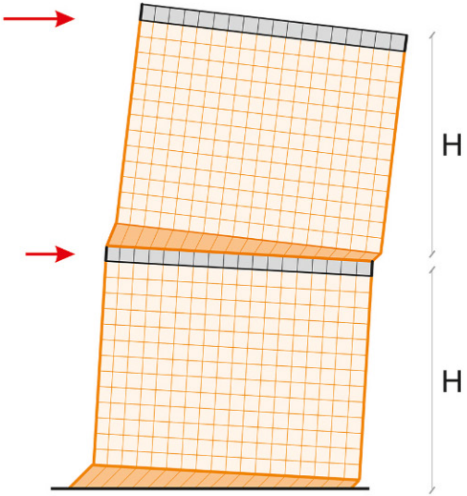
- Resist shear forces at base

Screws in joint

- Resist sliding forces between panels



Deformation Behavior



Source: Upgraded Model, Rinaldi et al. 2021

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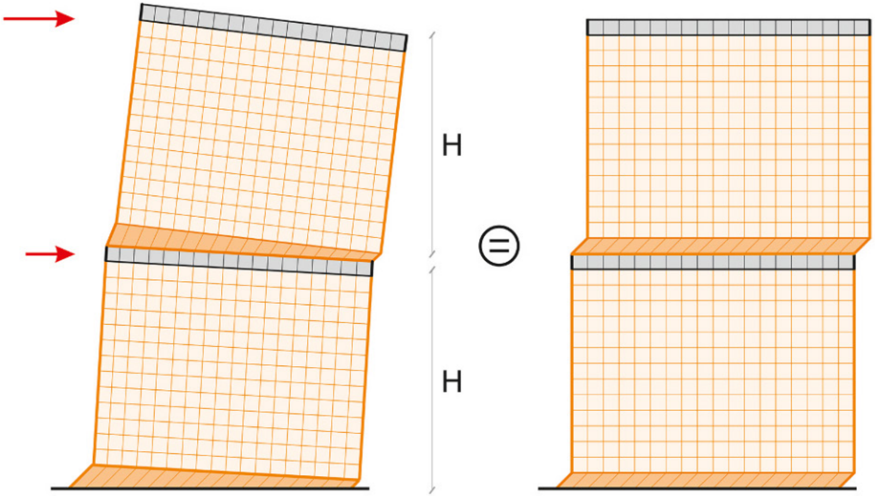

Sliding

Source: Upgraded Model, Rinaldi et al. 2021

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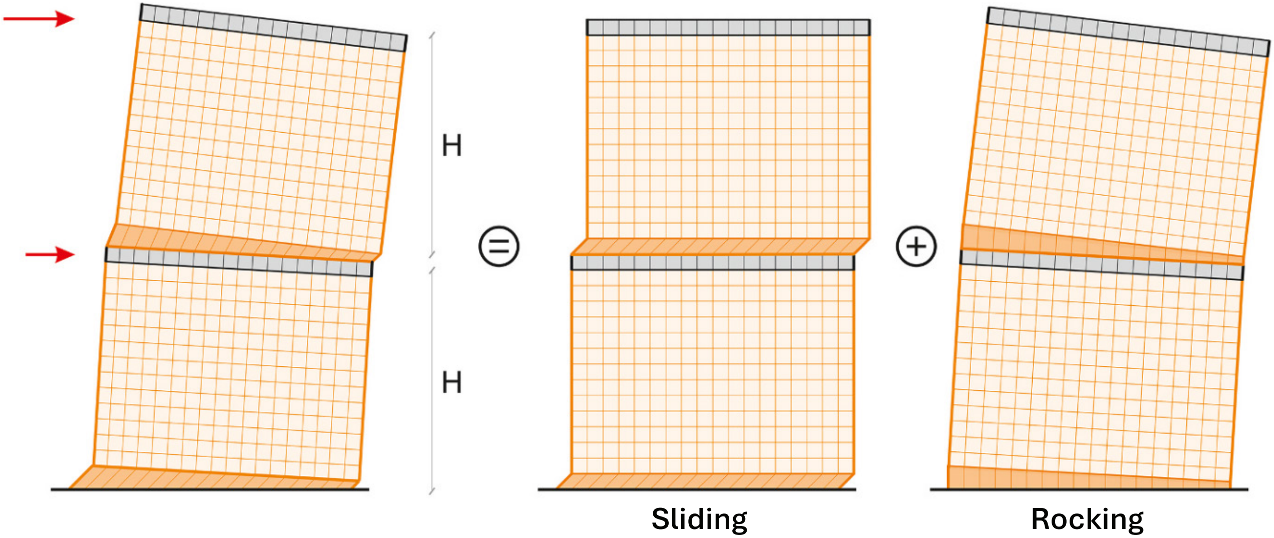

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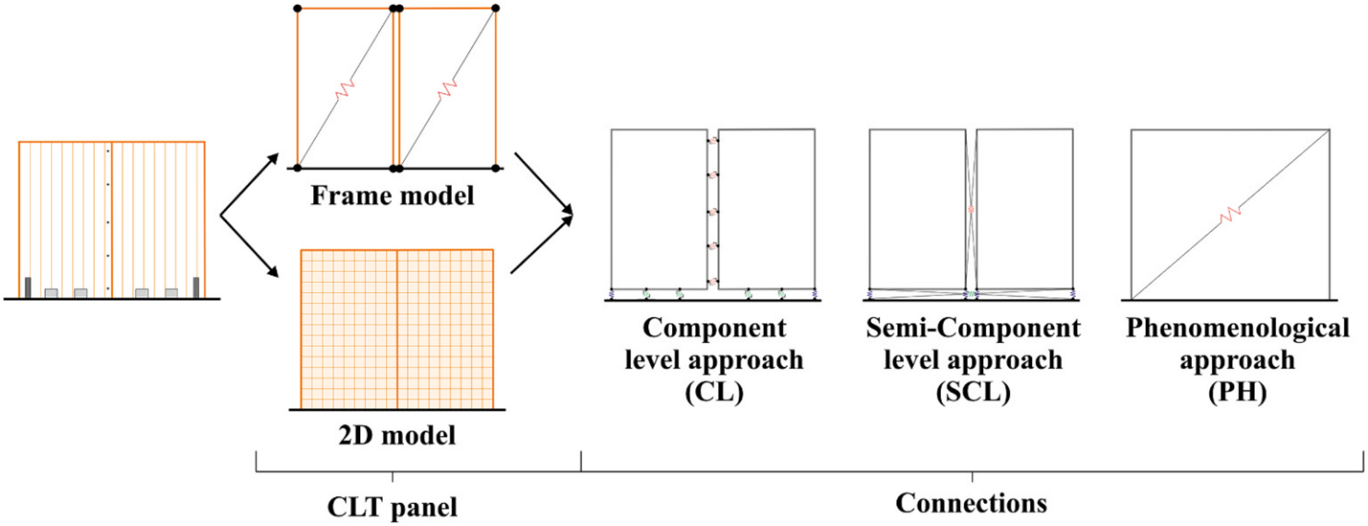
Modelling Strategies



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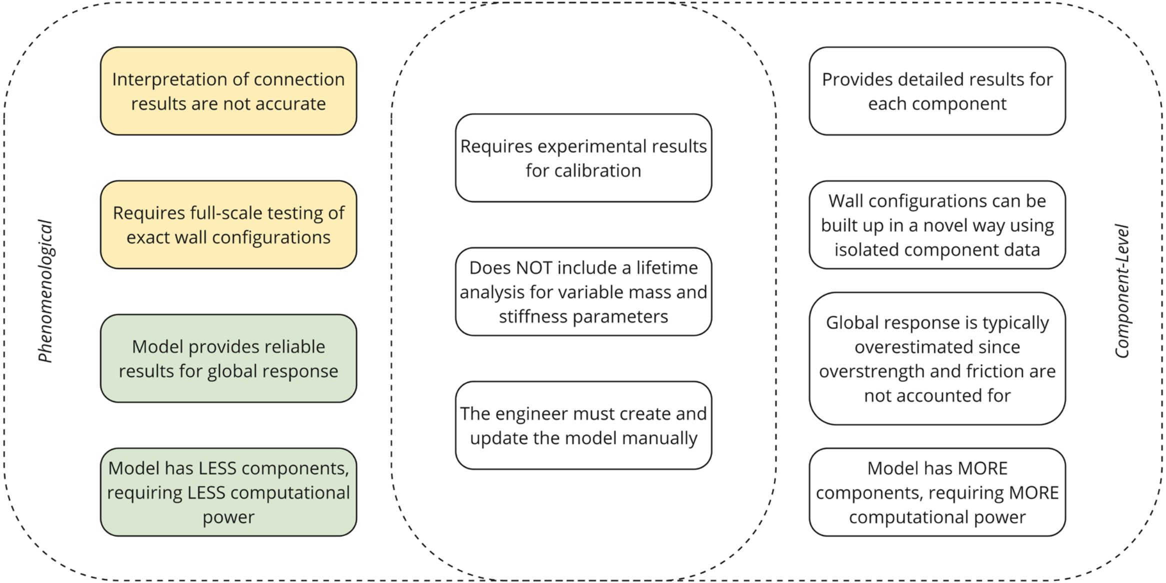

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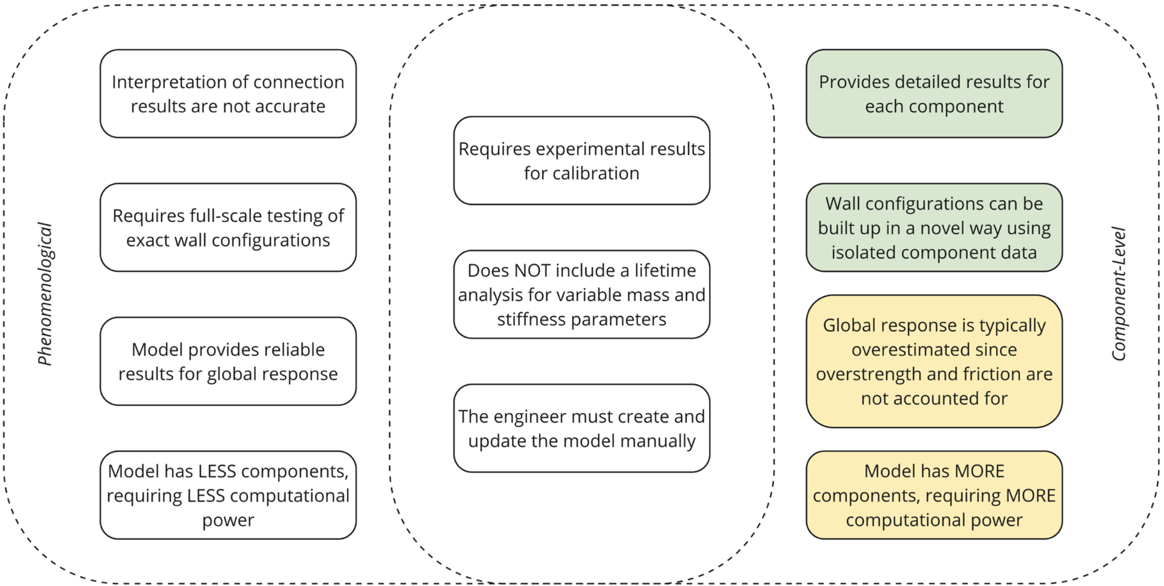
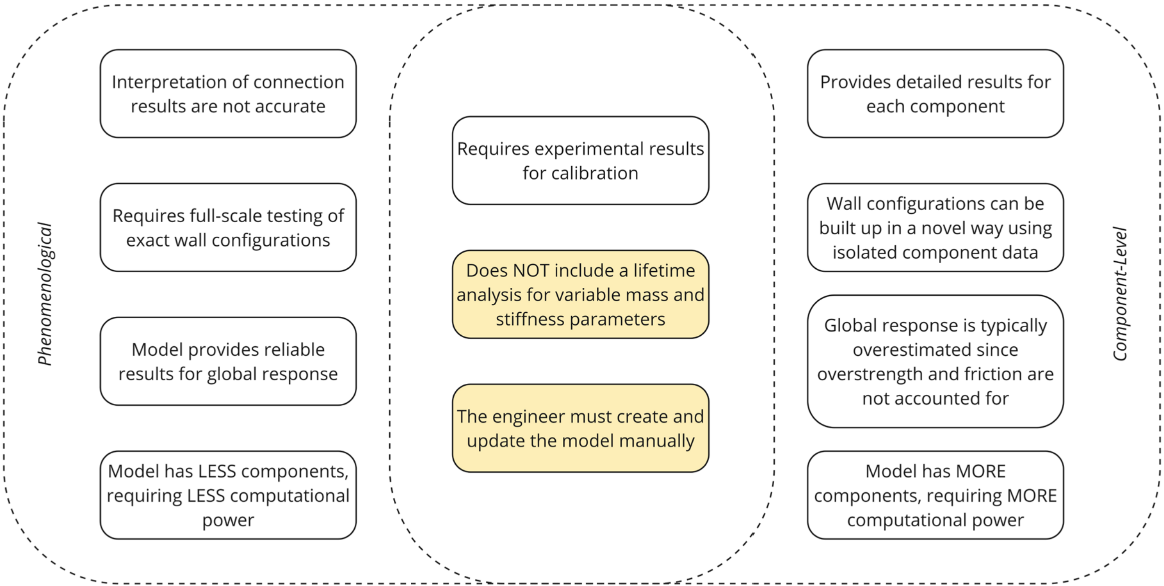
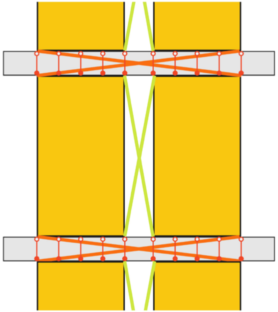


Modelling Strategies



Modelling Strategies

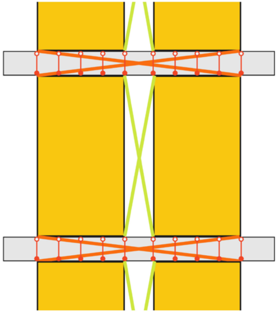
Follesa et al. 2013



Truss and links for wall-to-floor joints
Truss for wall-to-wall joints
Floor stiffness modelled with truss
Rigid CLT panels
Includes friction in angle brackets
Neglects rocking

Modelling Strategies

Follesa et al. 2013



Truss and links for wall-to-floor joints
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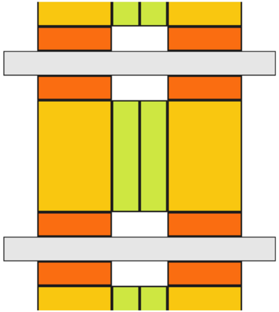
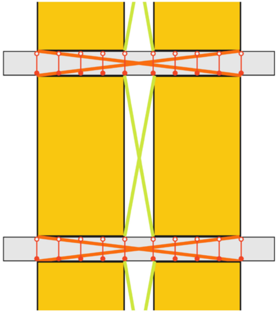
Christovasilis et al. 2020



Horizontal strips for wall-floor joints
Vertical strips for wall-wall joints
Floor stiffness modelled as 2D strip
Rigid CLT panels
Neglects friction
Neglects rocking

Modelling Strategies

Follesa et al. 2013



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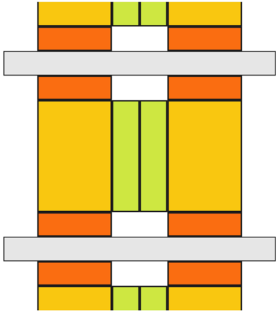
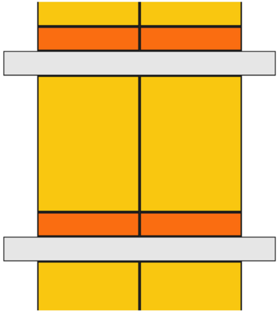


Horizontal strips for wall-floor joints
Vertical strips for wall-wall joints
Floor stiffness modelled as 2D strip
Rigid CLT panels
Neglects friction
Neglects rocking

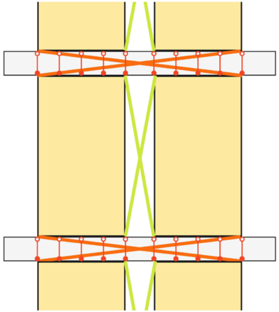
Rinaldi et al. 2021



Horizontal strips for wall-floor joints
Wall-wall joints in equivalent stiffness
Floor stiffness modelled as 2D strip
Rigid CLT panels
Neglects friction
Includes rocking in equivalent stiffness

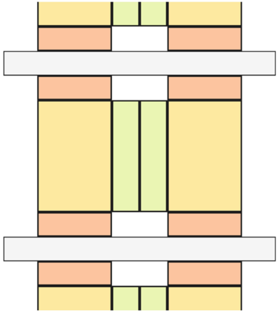
Modelling Strategies

Follesa et al. 2013



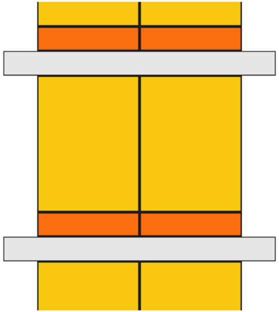
Truss and links for wall-to-floor joints
Truss for wall-to-wall joints
Floor stiffness modelled with truss
Rigid CLT panels
Includes friction in angle brackets
Neglects rocking

Christovasilis et al. 2020



Horizontal strips for wall-floor joints
Vertical strips for wall-wall joints
Floor stiffness modelled as 2D strip
Rigid CLT panels
Neglects friction
Neglects rocking

Rinaldi et al. 2021



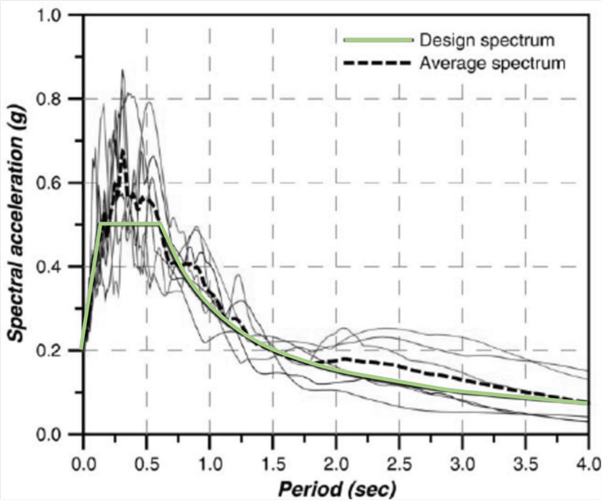
Horizontal strips for wall-floor joints
Wall-wall joints in equivalent stiffness
Floor stiffness modelled as 2D strip
Rigid CLT panels
Neglects friction
Includes rocking in equivalent stiffness

Full Structure Analysis

What is required for full structure analysis?

Seismic Parameters

- Spectral acceleration



Full Structure Analysis

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Seismic Parameters

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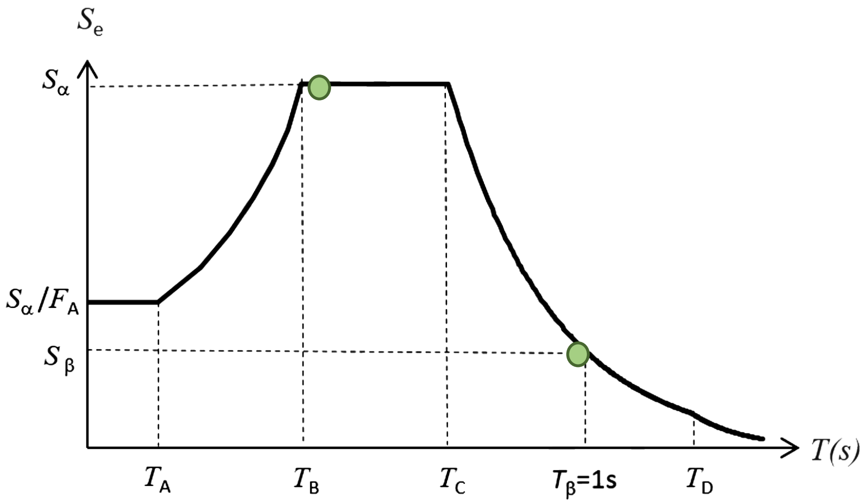


Full Structure Analysis

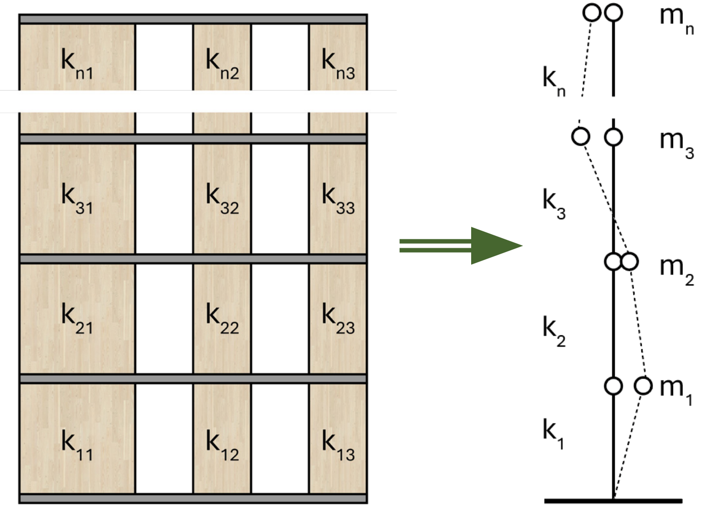
What is required for full structure analysis?

Seismic Parameters

- Spectral acceleration

Structural Parameters

- Mass and stiffness distribution



Eigen model

Full Structure Analysis

What is required for full structure analysis?

Seismic Parameters

- Spectral acceleration

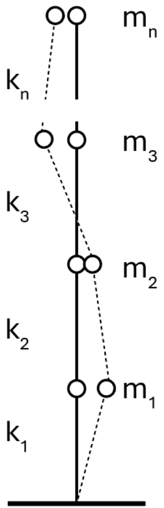
Structural Parameters

- Mass and stiffness distribution
- Building period

$$\omega = \sqrt{\frac{m}{k}} = eigen\ vector$$

$$T = 2\pi\omega$$

Relationship b/t eigen analysis and building period



Eigen model

Full Structure Analysis

What is required for full structure analysis?

Seismic Parameters

- Spectral acceleration

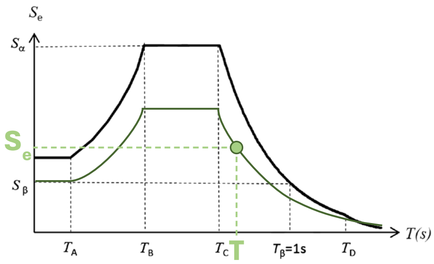
Structural Parameters

- Mass and stiffness distribution
- Building period
- Seismic coefficient

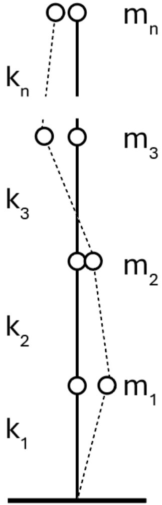
$$\omega = \sqrt{\frac{m}{k}} = eigen\ vector$$

$$T = 2\pi\omega$$

Relationship b/t eigen analysis and building period



Determining the seismic coefficient from the design spectra and the building period



Eigen model

Full Structure Analysis

What is required for full structure analysis?

Seismic Parameters

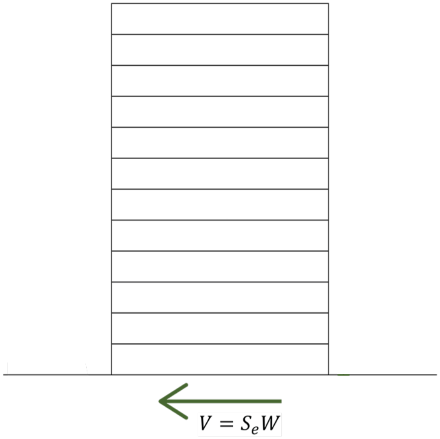
- Spectral acceleration

Structural Parameters

- Mass and stiffness distribution
- Building period
- Seismic coefficient

Force Distribution

- Base shear



Full Structure Analysis

What is required for full structure analysis?

Seismic Parameters

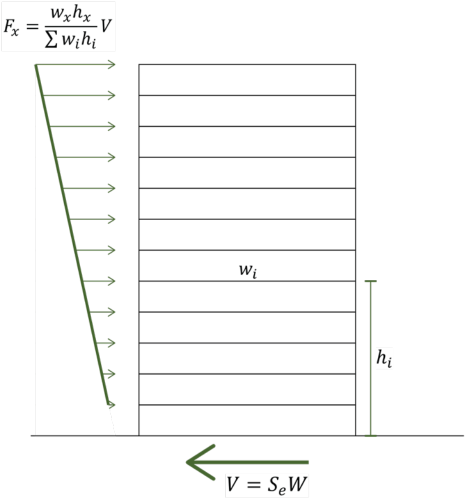
- Spectral acceleration

Structural Parameters

- Mass and stiffness distribution
- Building period
- Seismic coefficient

Force Distribution

- Base shear
- Distribute to floors based on story height and weight



Full Structure Analysis

What is required for full structure analysis?

Seismic Parameters

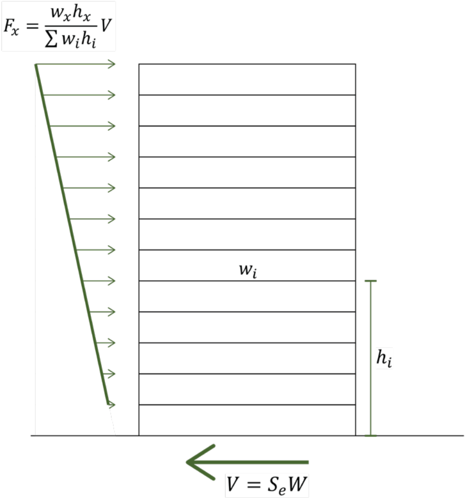
- Spectral acceleration

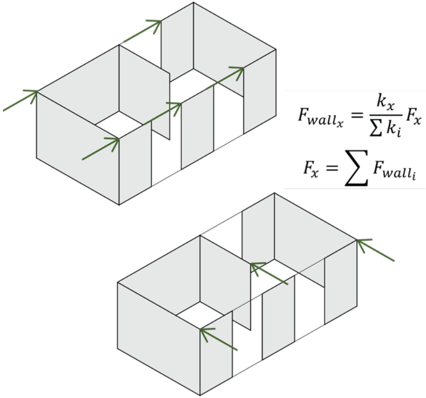
Structural Parameters

- Mass and stiffness distribution
- Building period
- Seismic coefficient

Force Distribution

- Base shear
- Distribute to floors based on story height and weight
- Distribute to walls based on effective stiffness





Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:

Source: SOFIE project, Ceccotti et al. 2013

Seven story test structure from the SOFIE project

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures

Seven story test structure from the SOFIE project

Nail failures at hold-downs

Source: SOFIE project, Ceccotti et al. 2013

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
    - Fastener failures
    - Fastener withdrawals

Nail failures at hold-downs

Nail withdrawal at angle brackets

Source: SOFIE project, Ceccotti et al. 2013

Seven story test structure from the SOFIE project

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Seven story test structure from the SOFIE project

Nail failures at hold-downs

Nail withdrawal at angle brackets

Wood crushing under hold-downs

Source: SOFIE project, Ceccotti et al. 2013

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution

Facade renovation

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution

Facade renovation

Change in occupancy

Lifetime Analysis

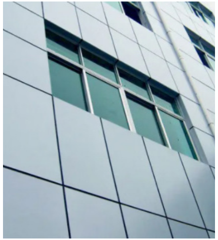
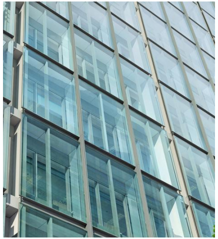
How can these events or time variables impact seismic performance?

Previous Seismic Event

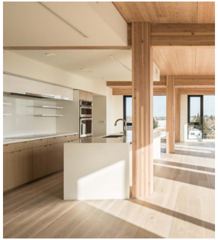
- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

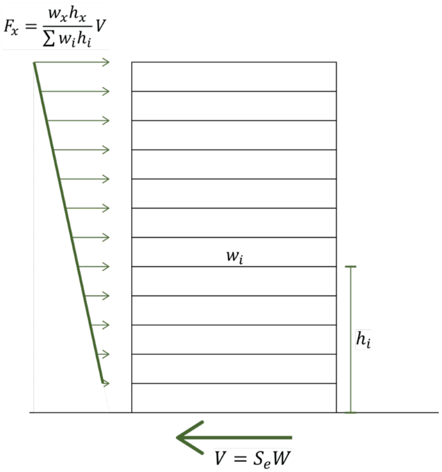
- Mass distribution

Facade renovation




Change in occupancy



Change in mass and forces

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

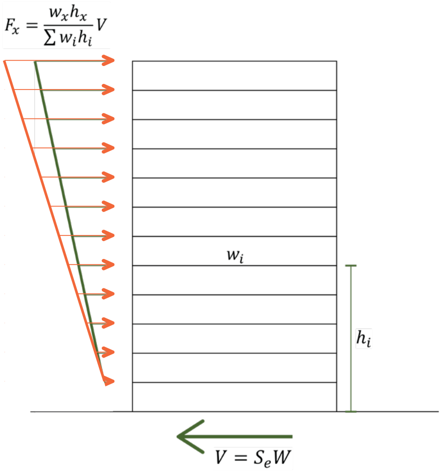
- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution

Facade renovation

Change in occupancy



Change in mass and forces

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution
- Stiffness change

Replace old connections

Lifetime Analysis

How can these events or time variables impact seismic performance?

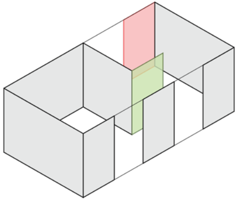
Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution
- Stiffness change

Replace old connections



Add, remove, or replace walls

Lifetime Analysis

How can these events or time variables impact seismic performance?

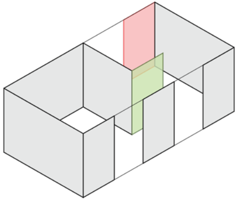
Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

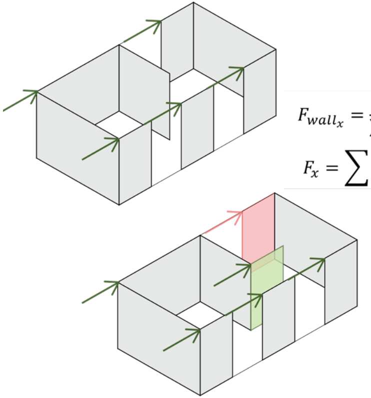
Future Renovation

- Mass distribution
- Stiffness change

Replace old connections



Add, remove, or replace walls



$$F_{wall_x} = \frac{k_x}{\sum k_i} F_x$$

$$F_x = \sum F_{wall_i}$$

Change in stiffness distribution

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution
- Stiffness change

Biological Degradation

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution
- Stiffness change

Biological Degradation

- Stiffness and mass loss in CLT

Deterioration causes loss in mass and stiffness

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

- Mass distribution
- Stiffness change

Biological Degradation

- Stiffness and mass loss in CLT

Deterioration causes loss in mass and stiffness

Related to moisture exposure and time

Lifetime Analysis

How can these events or time variables impact seismic performance?

Previous Seismic Event

- Stiffness reduction from:
  - Fastener failures
  - Fastener withdrawals
  - Wood crushing

Future Renovation

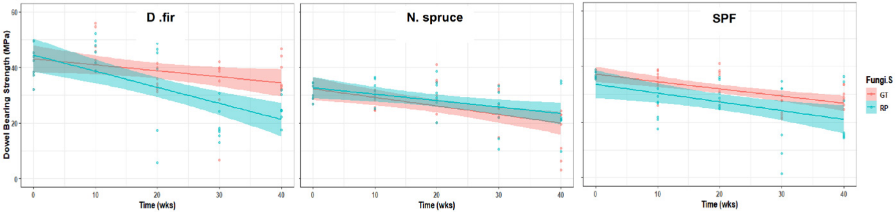
- Mass distribution
- Stiffness change

Biological Degradation

- Stiffness and mass loss in CLT
- Embedment strength of fasteners in connections

Deterioration causes loss in mass and stiffness

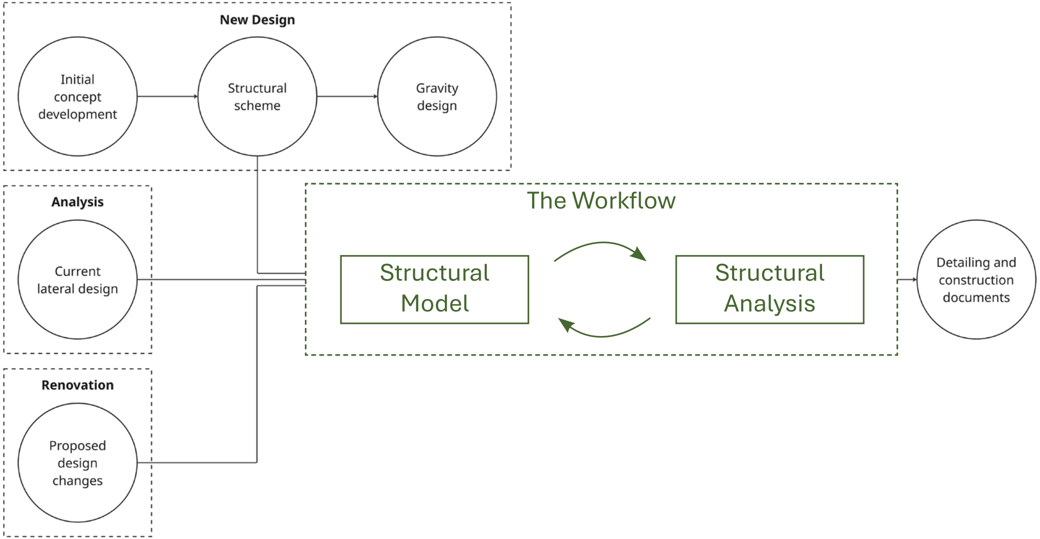
Related to moisture exposure and time



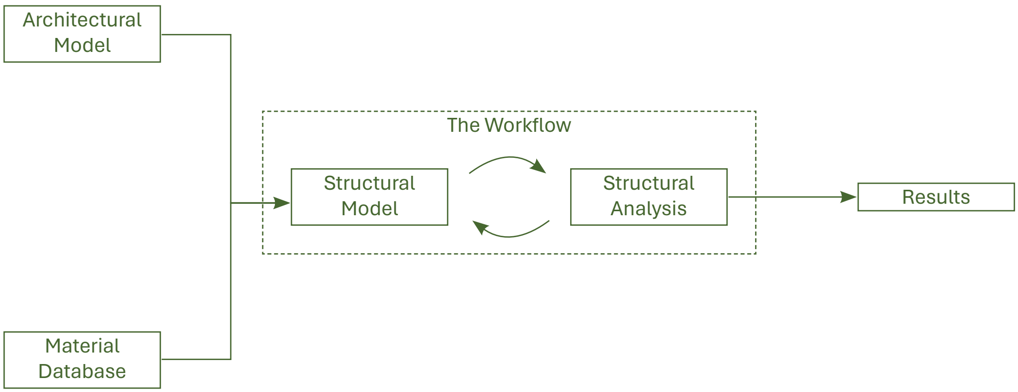
Linear regression for dowel bearing strength over time of fungal exposure for three species of wood: Douglas Fir, Norway Spruce, and Spruce Pine Fir (Source: Udele et al. 2024)

The Workflow

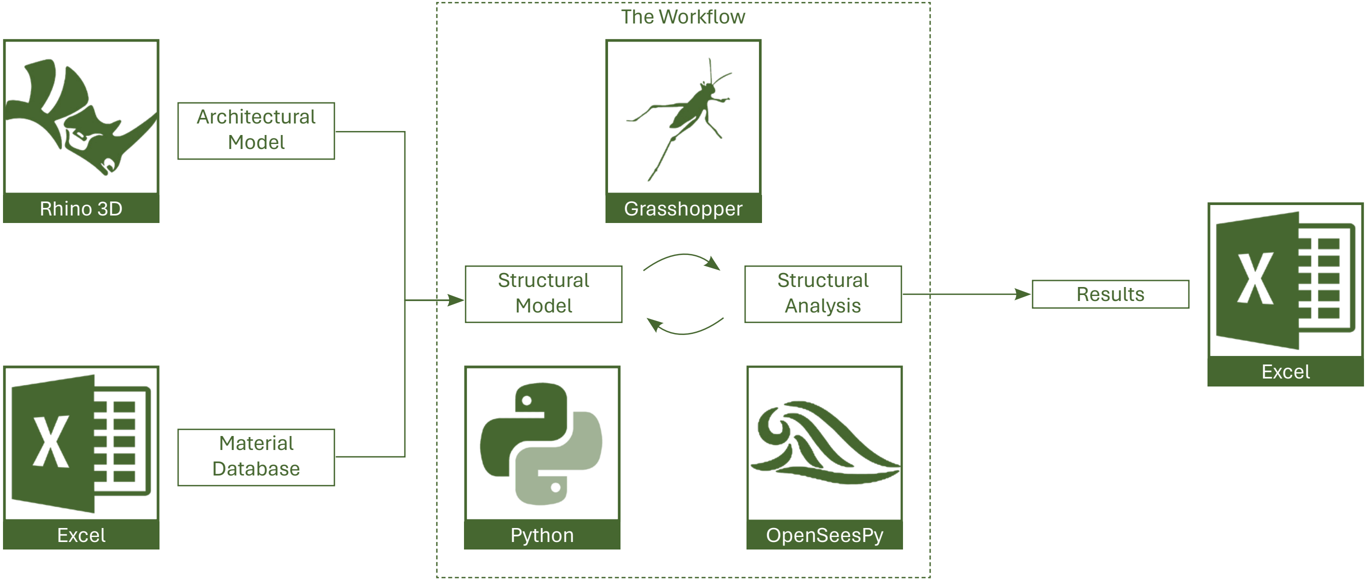
When to use the tool?



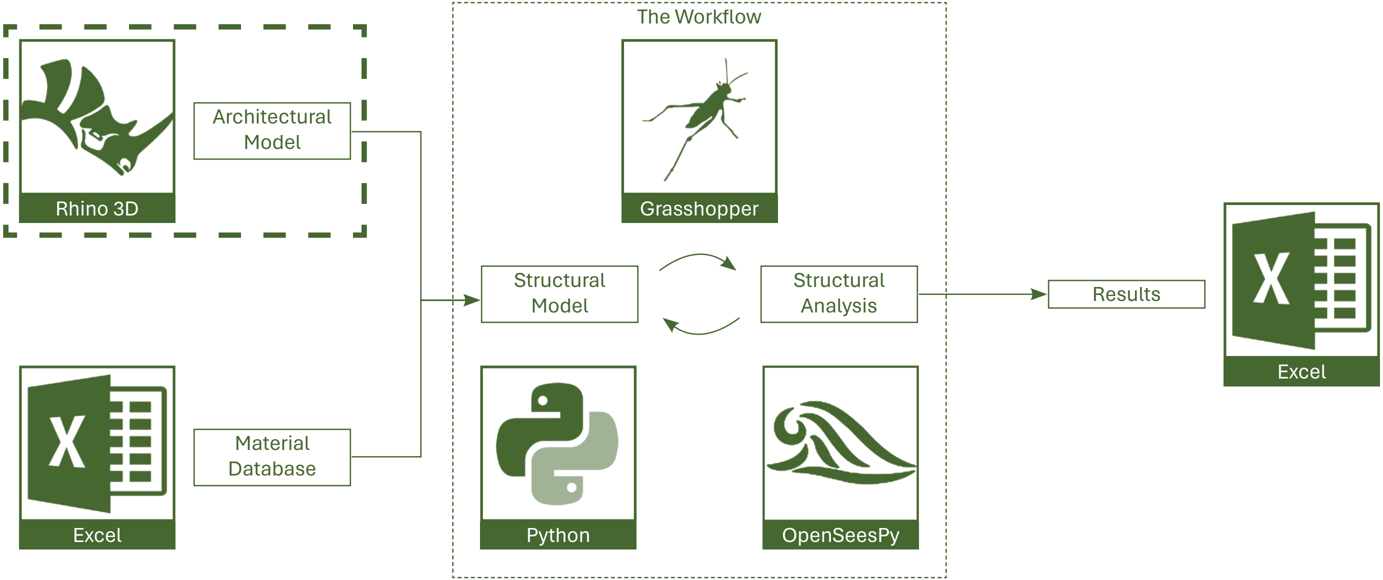
The Workflow



Programs and Workflow



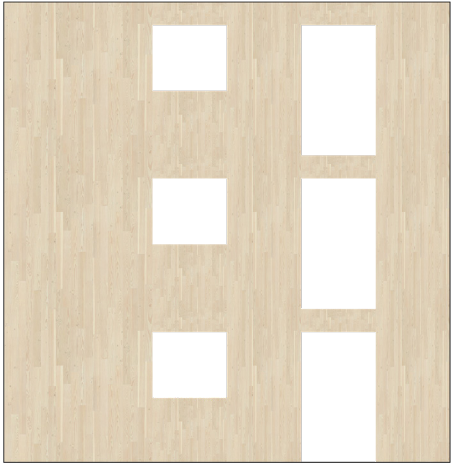
Programs and Workflow



Model Generation

Create Geometry

Wall Geometry

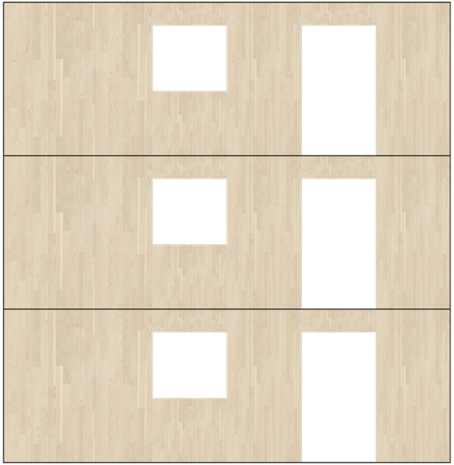


Model Generation

Create Geometry

Wall Geometry

- Split at each floor

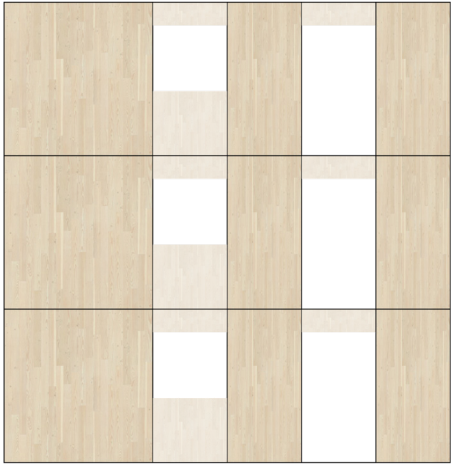


Model Generation

Create Geometry

Wall Geometry

- Split at each floor
- Ignore walls with openings



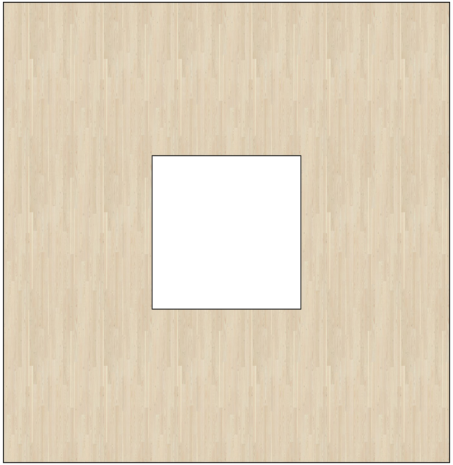
Model Generation

Create Geometry

Wall Geometry

- Split at each floor
- Ignore walls with openings

Floor Geometry



Model Generation

Create Geometry

Wall Geometry

- Split at each floor
- Ignore walls with openings

Floor Geometry

- Ignore shafts and openings

Model Generation

Create Geometry

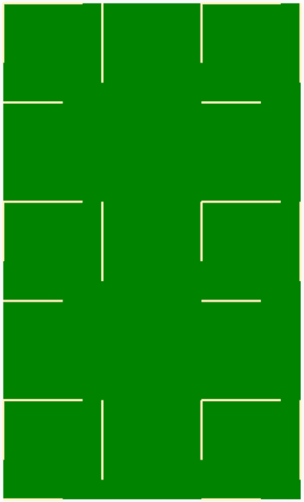
Wall Geometry

- Split at each floor
- Ignore walls with openings

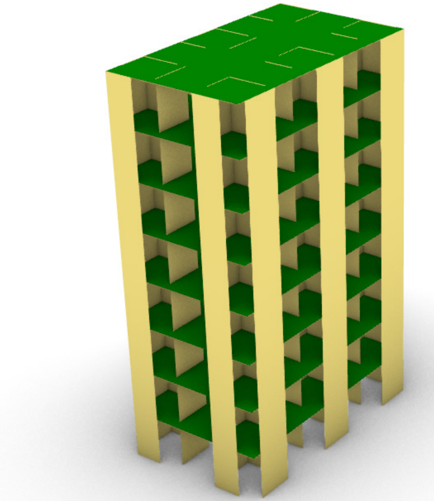
Floor Geometry

- Ignore shafts and openings

Modelled with Rectangle 3D

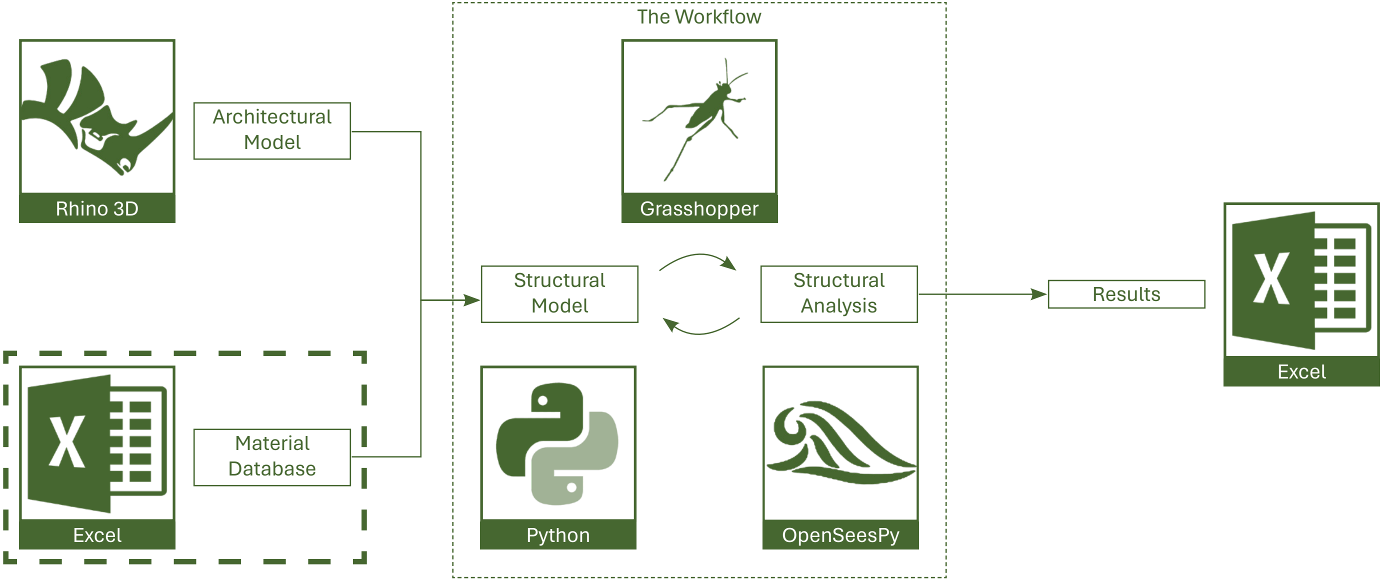


Plan view of example structure



3D model of example structure

Programs and Workflow



Materials Database

CLT properties

Raw Timber Properties

- Species

Materials Database

CLT properties

Raw Timber Properties

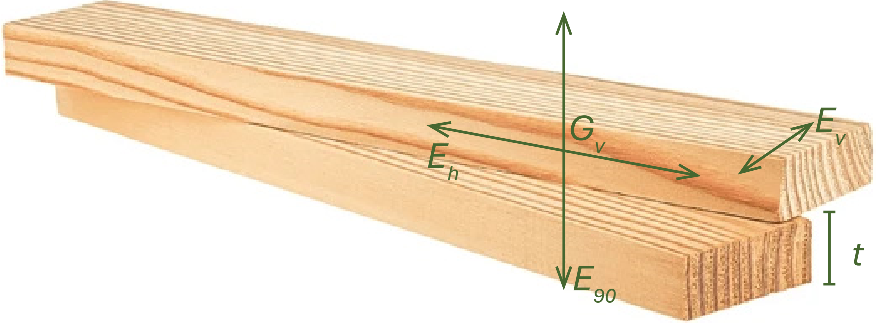
- Species
- Board thicknesses

Materials Database

CLT properties

Raw Timber Properties

- Species
- Board thicknesses
- Raw timber properties



Materials Database

CLT properties

Raw Timber Properties

- Species
- Board thicknesses
- Raw timber properties

Panel Properties

Materials Database

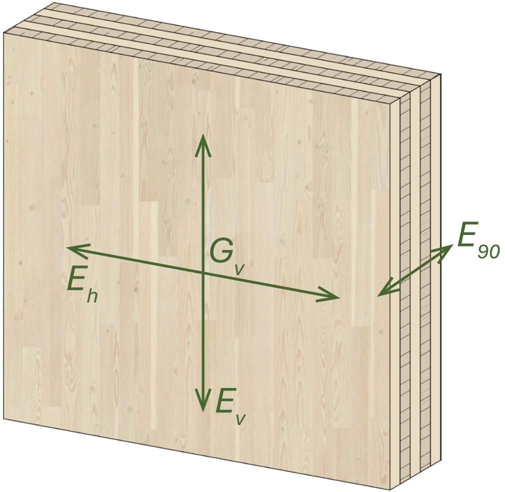
CLT properties

Raw Timber Properties

- Species
- Board thicknesses
- Raw timber properties

Panel Properties

- Elastic and shear modulus



Materials Database

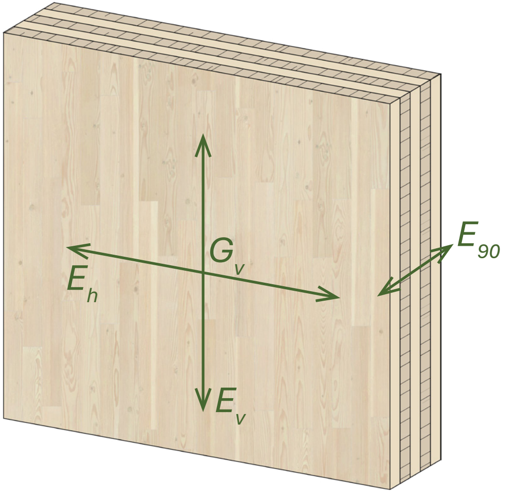
CLT properties

Raw Timber Properties

- Species
- Board thicknesses
- Raw timber properties

Panel Properties

- Elastic and shear modulus
  - Calculated via research



Elastic Moduli calculated via Blass et al. 2004

Shear Modulus calculated via Bogensperger et al. 2016

Materials Database

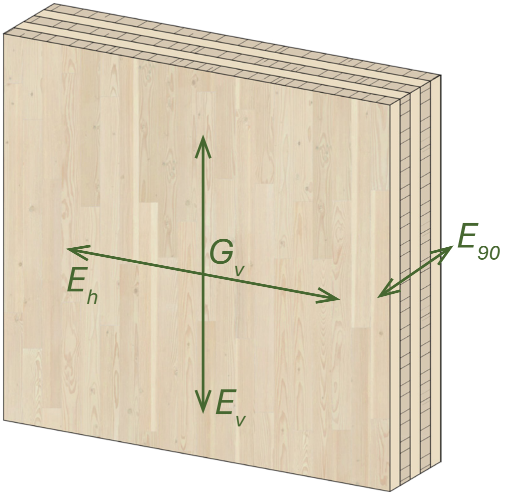
CLT properties

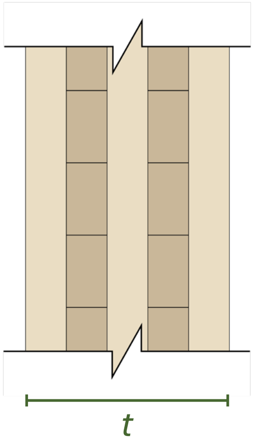
Raw Timber Properties

- Species
- Board thicknesses
- Raw timber properties

Panel Properties

- Elastic and shear modulus
  - Calculated via research
- Thickness of panel





Materials Database

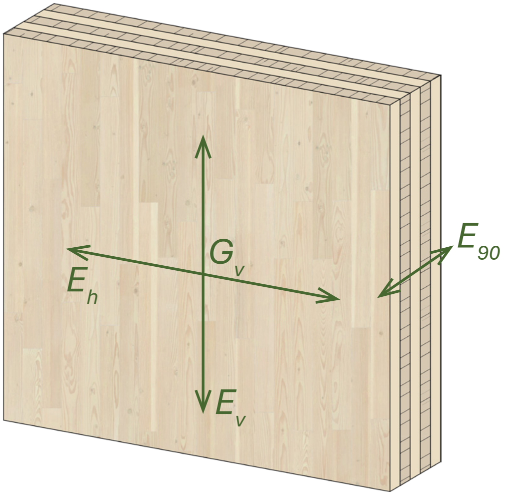
CLT properties

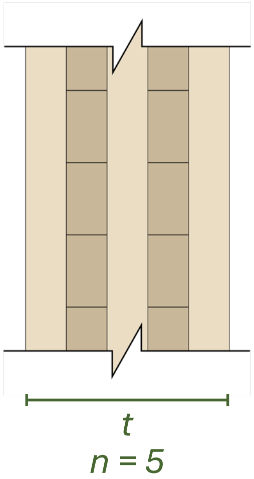
Raw Timber Properties

- Species
- Board thicknesses
- Raw timber properties

Panel Properties

- Elastic and shear modulus
  - Calculated via research
- Thickness of panel
- Number of layers





Materials Database

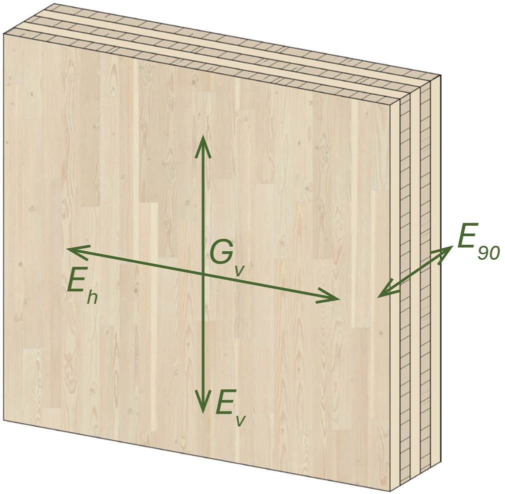
CLT properties

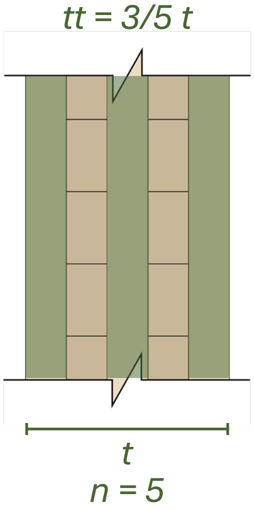
Raw Timber Properties

- Species
- Board thicknesses
- Raw timber properties

Panel Properties

- Elastic and shear modulus
  - Calculated via research
- Thickness of panel
- Number of layers
- Layer thickness ratio
  - Calculated via research





Materials Database

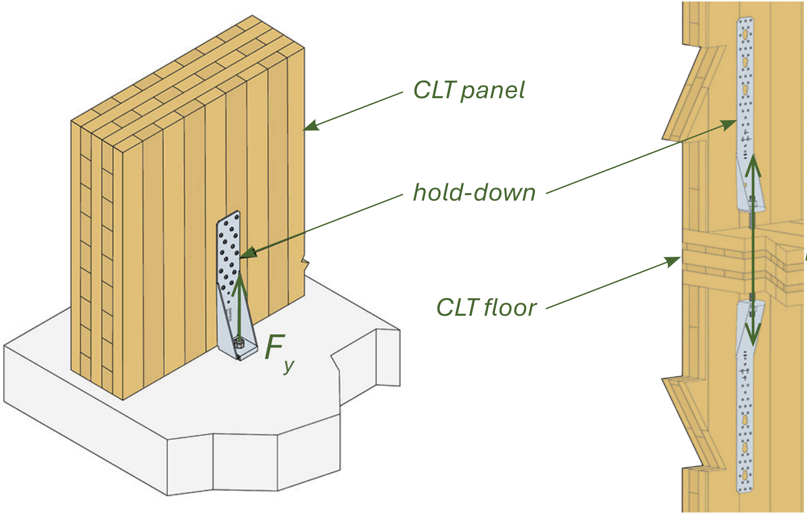
Hold Down properties

Connection Properties

- Yielding load and deflection
- Stiffness in both directions
- Plate thickness
- Overstrength

Fastener Properties

- Length
- Diameter
- Amount



Source: Simpson Strong Tie

Materials Database

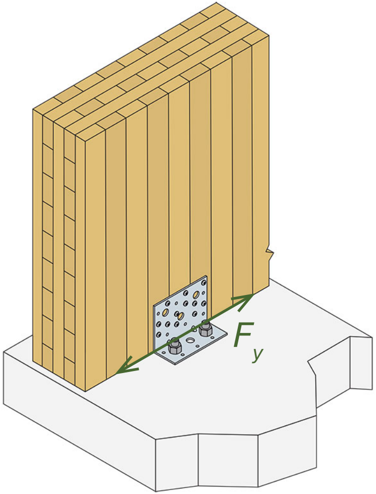
Angle Bracket properties

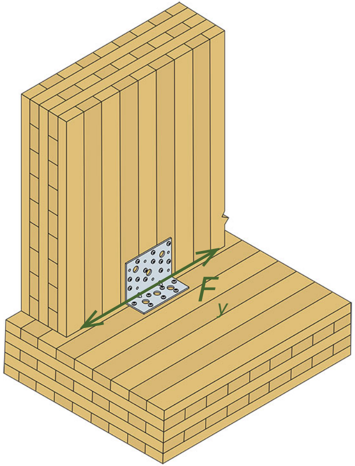
Connection Properties

- Yielding load and deflection
- Stiffness in both directions
- Plate thickness
- Overstrength

Fastener Properties

- Length
- Diameter
- Amount





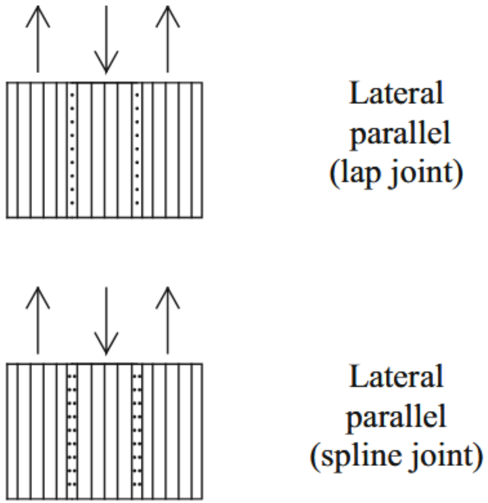
Source: Simpson Strong Tie

Materials Database

Screw Joint properties

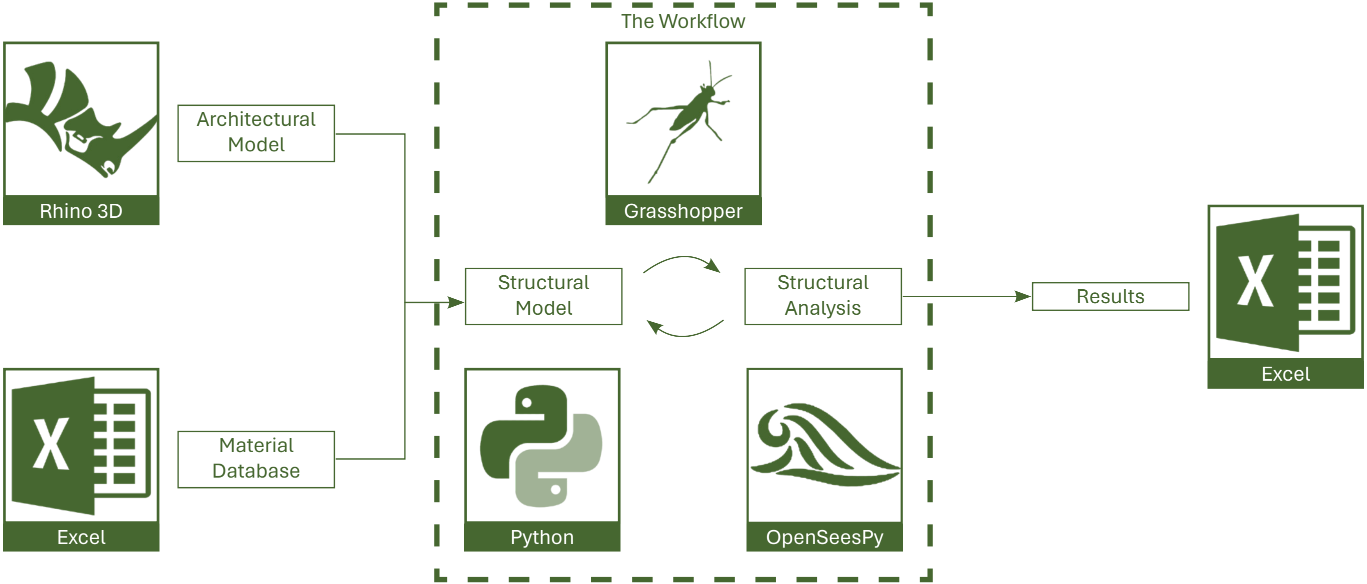
Joint Connection Properties

- Joint type (splice or lap)
- Load direction (vertical in plane)
- Orientation (Parallel)
- Yield strength
- Stiffness

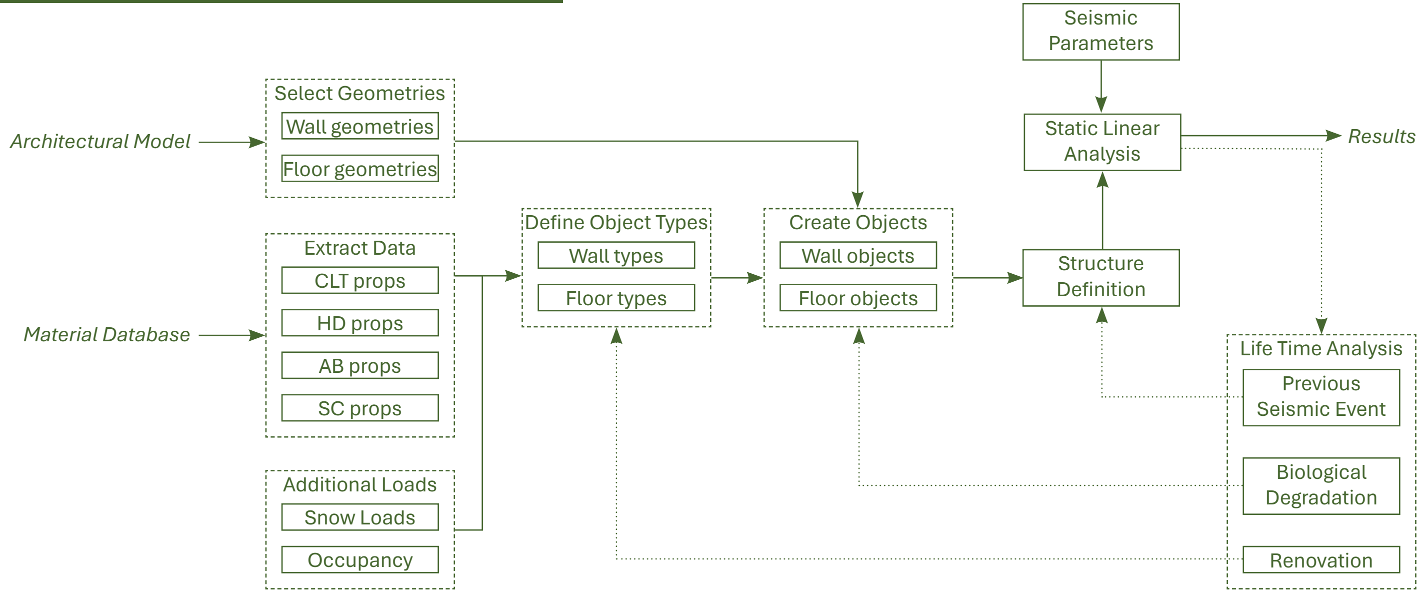


Source: Gavric et al. 2015

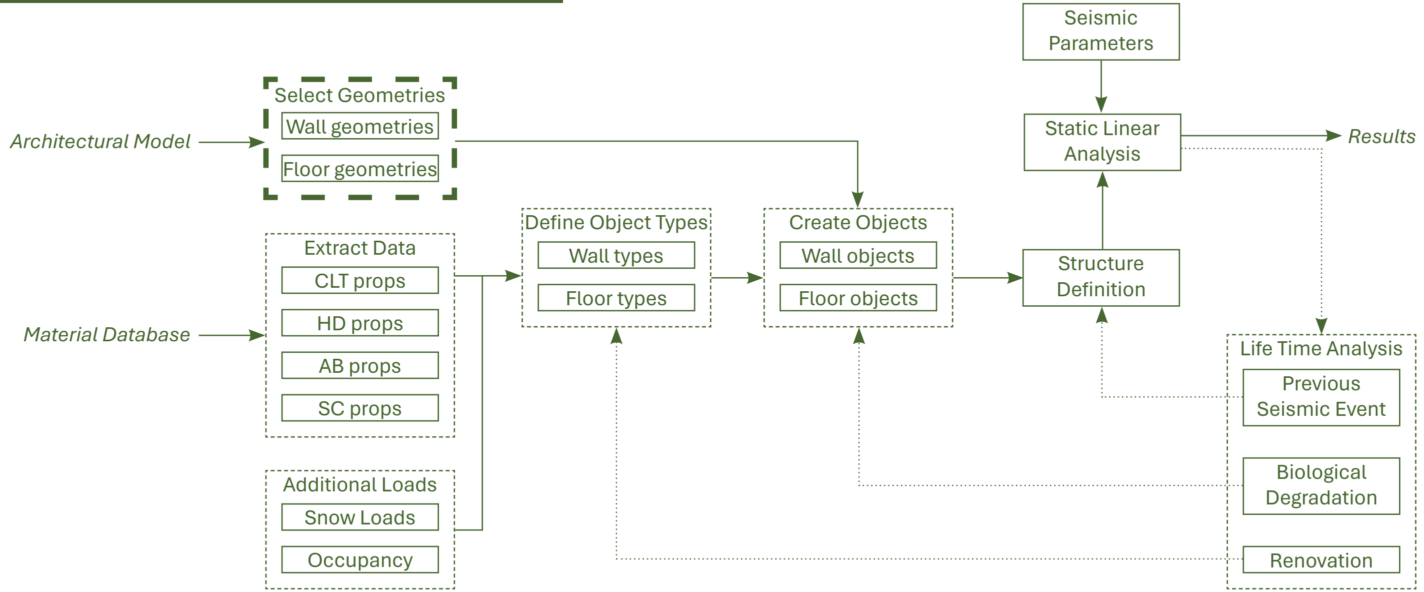
Programs and Workflow



The Workflow



The Workflow



Selecting Geometries

Organized by Layers

- Separate wall and floor layers

Rhino 3D

Walls

Floors

Selecting Geometries

Organized by Layers

- Separate wall and floor layers
- Separate by types into sublayers

Rhino 3D

- Walls
  - Wall type 1
  - Wall type 2
  - Wall type 3
  - Wall type 4
- Floors
  - Floor type 1
  - Floor type 2

Selecting Geometries

Organized by Layers

- Separate wall and floor layers
- Separate by types into sublayers

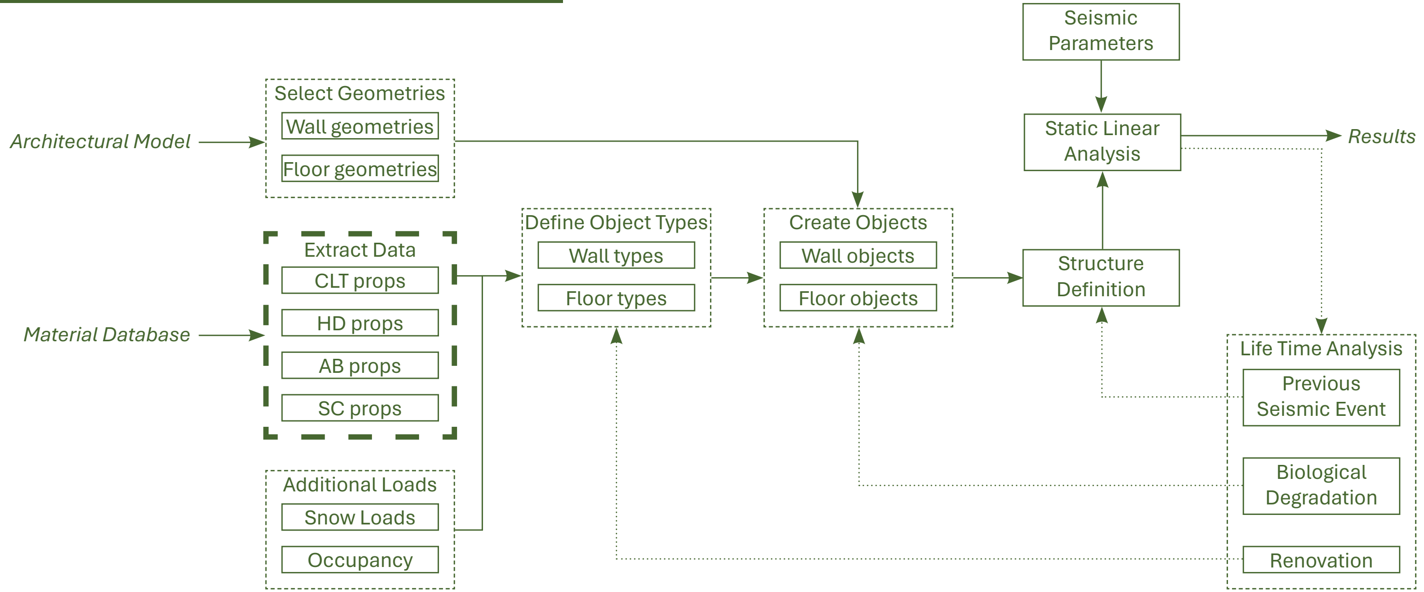
Bring into Grasshopper

Rhino 3D

- Walls
  - Wall type 1
  - Wall type 2
  - Wall type 3
  - Wall type 4
- Floors
  - Floor type 1
  - Floor type 2

Grasshopper

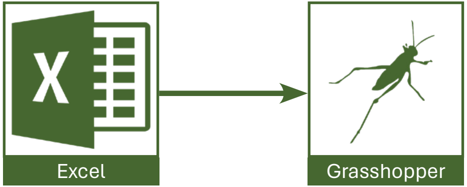
The Workflow



Model Generation

Import Material Data to Grasshopper

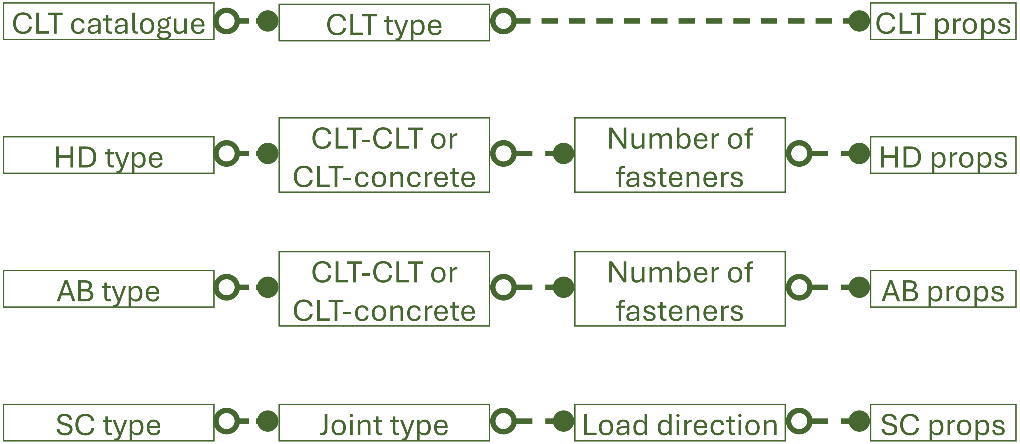
- Connect file path to materials database



Model Generation

Import Material Data to Grasshopper

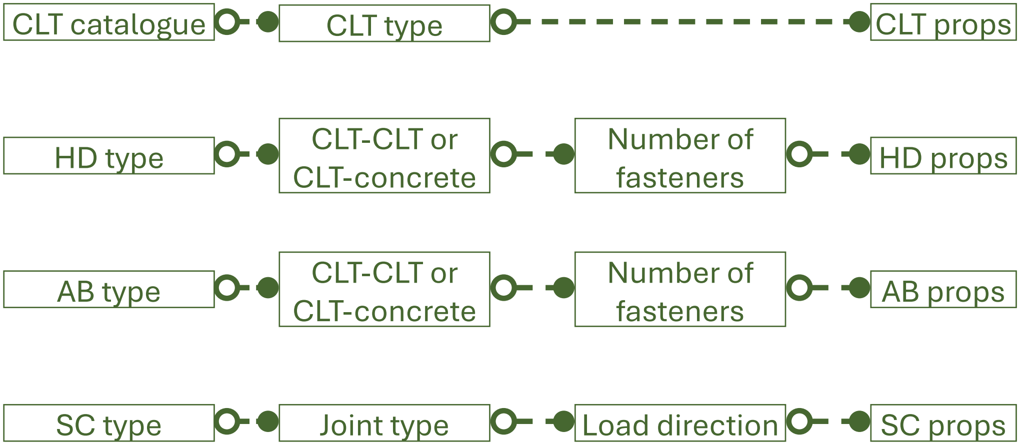
- Connect file path to materials database
- Select identifying properties to select CLT, HD, AB, or SC



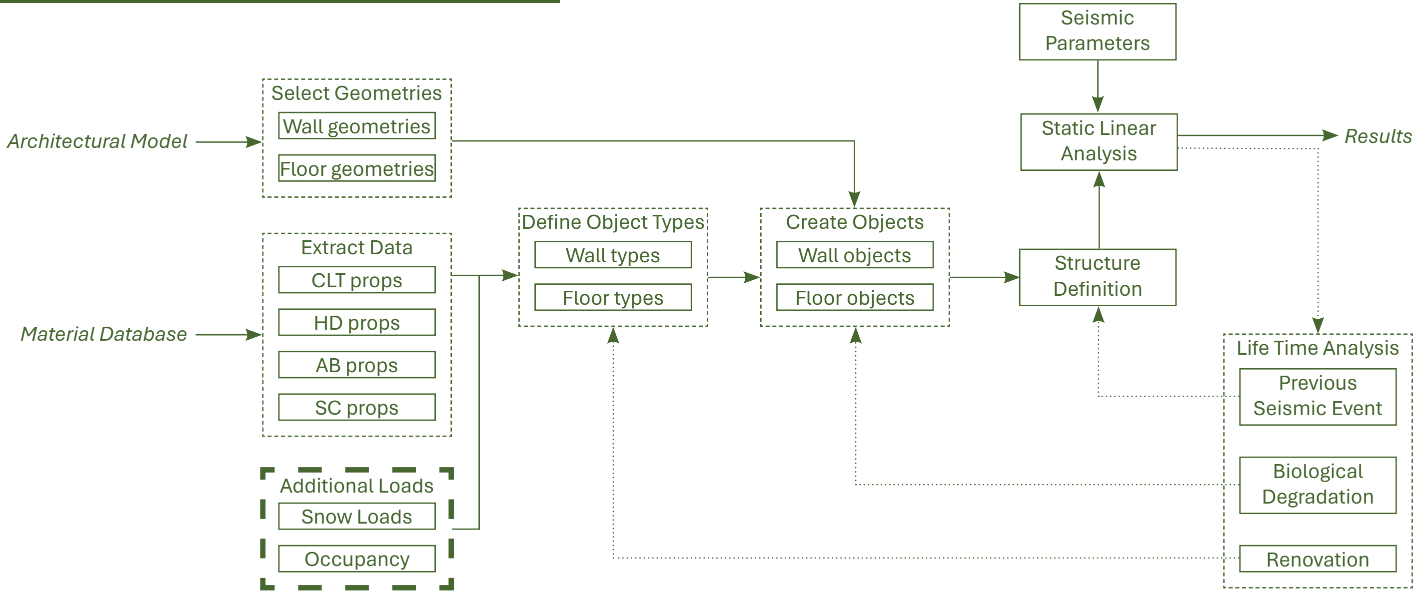
Model Generation

Import Material Data to Grasshopper

- Connect file path to materials database
- Select identifying properties to select CLT, HD, AB, or SC
- Mechanical and mass properties



The Workflow



Model Generation

Additional Variable Floor Loads

- Eurocodes require inclusion of reduced variable loads due to snow or occupancy types

Snow load

Variable load

Model Generation

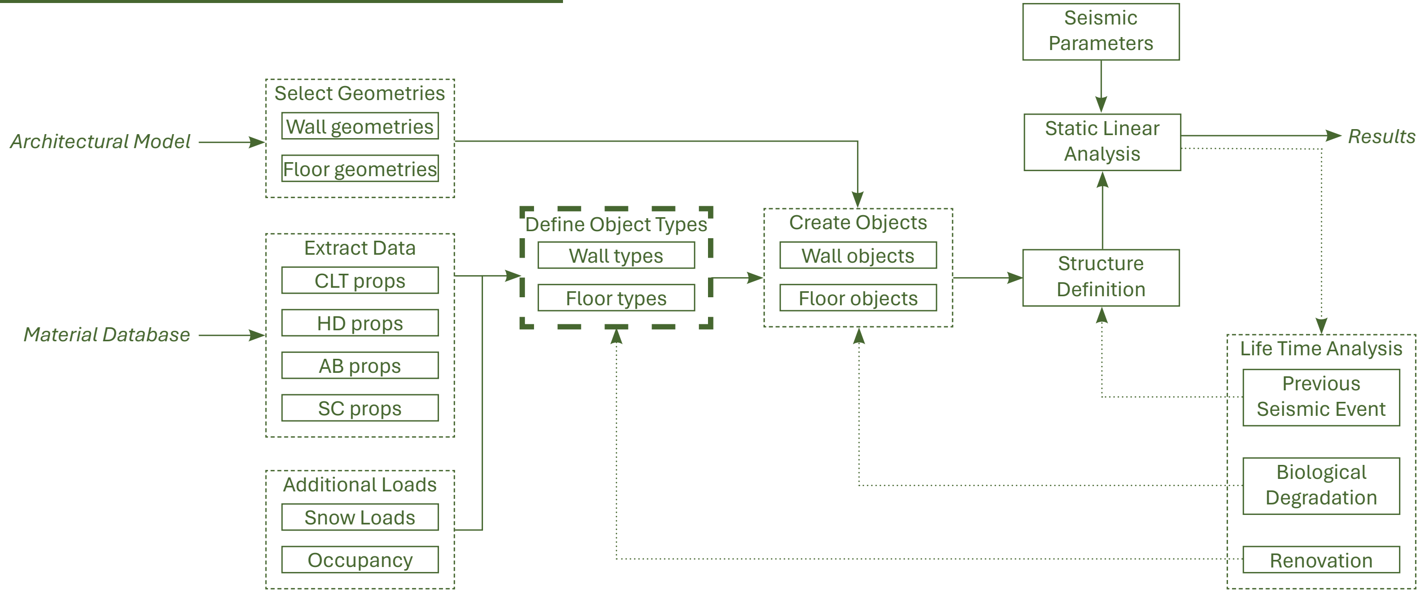
Additional Variable Floor Loads

- Eurocodes require inclusion of reduced variable loads due to snow or occupancy types
- Standard loads and reduction factors per Eurocodes provided, user can also input their own

Snow load

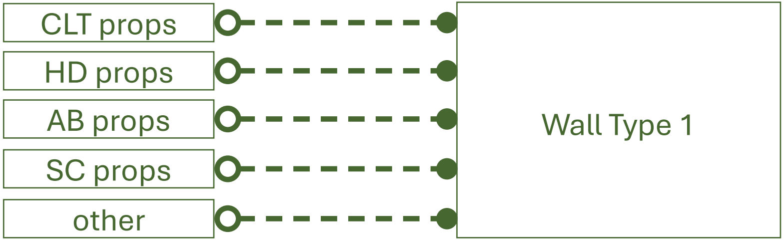
Variable load

The Workflow



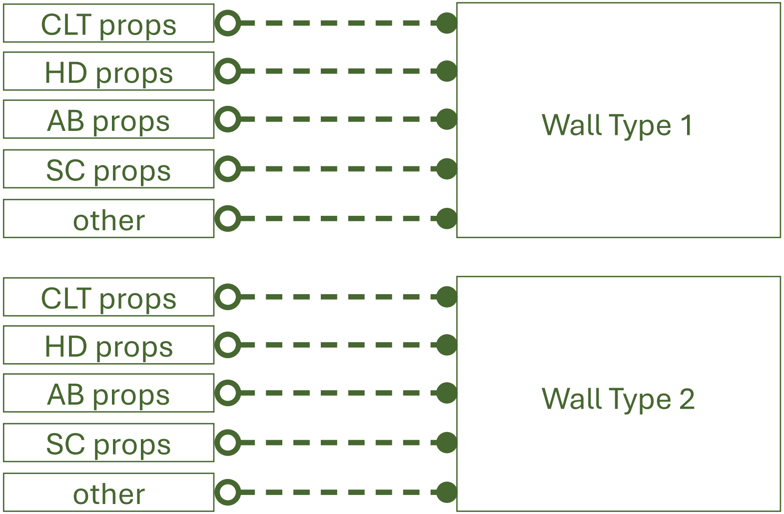
Model Generation

Wall and Floor Types



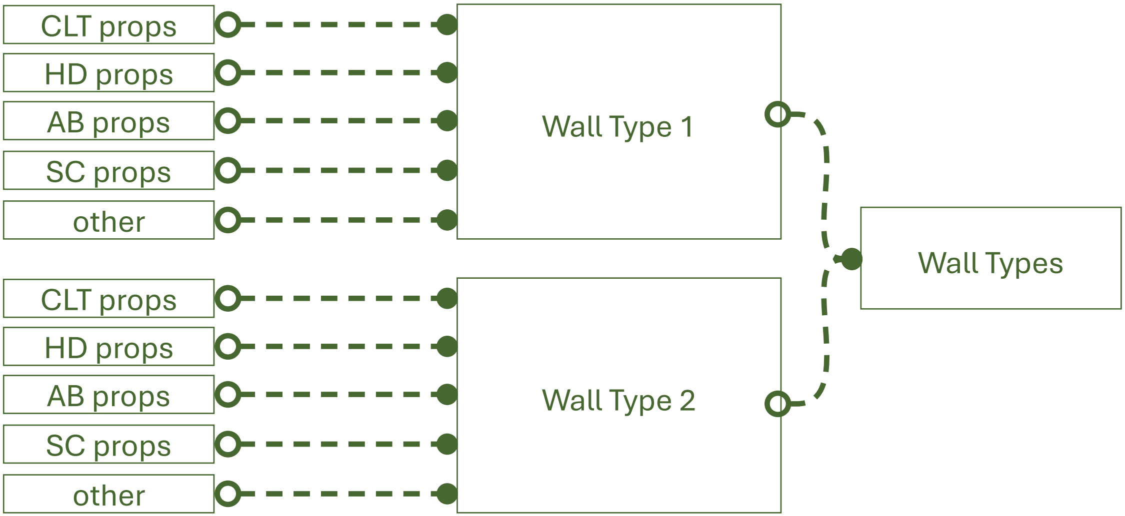
Model Generation

Wall and Floor Types



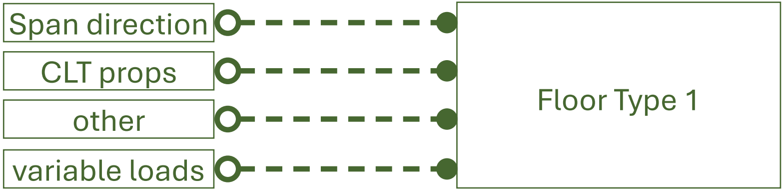
Model Generation

Wall and Floor Types



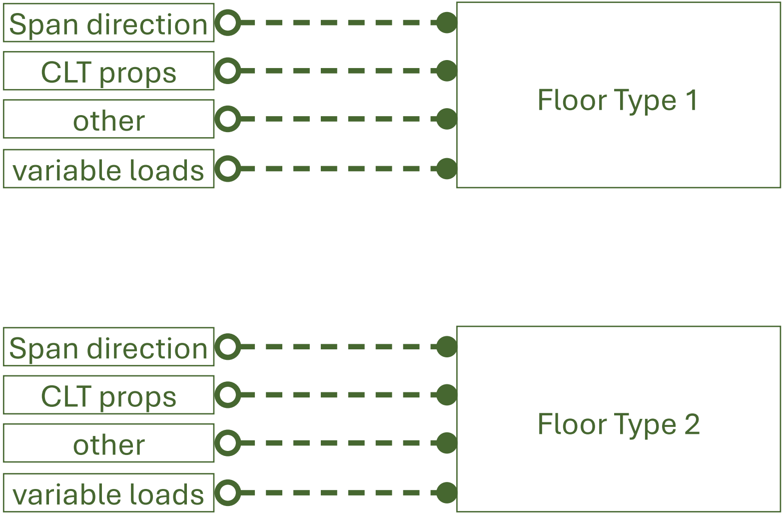
Model Generation

Wall and Floor Types



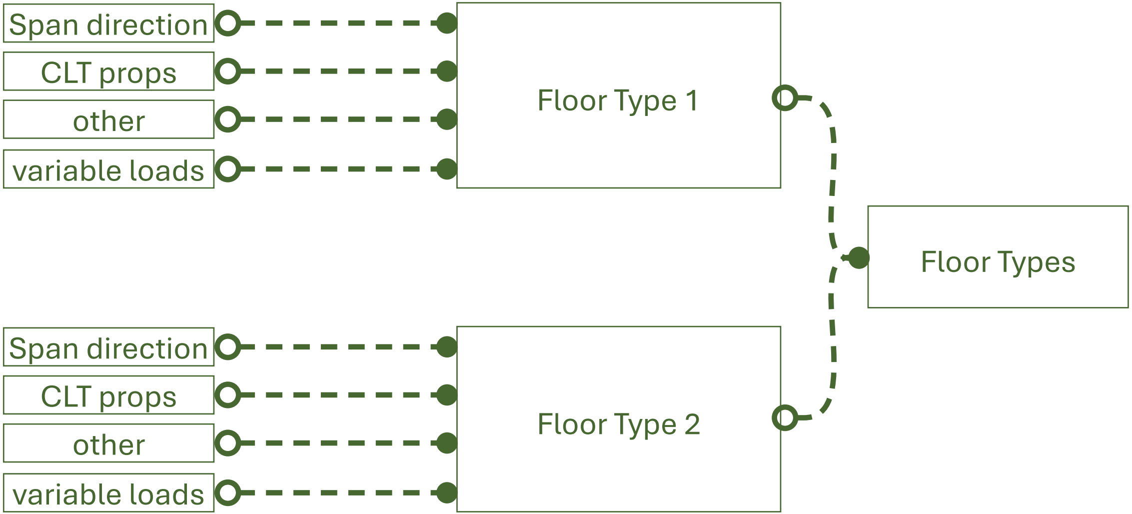
Model Generation

Wall and Floor Types

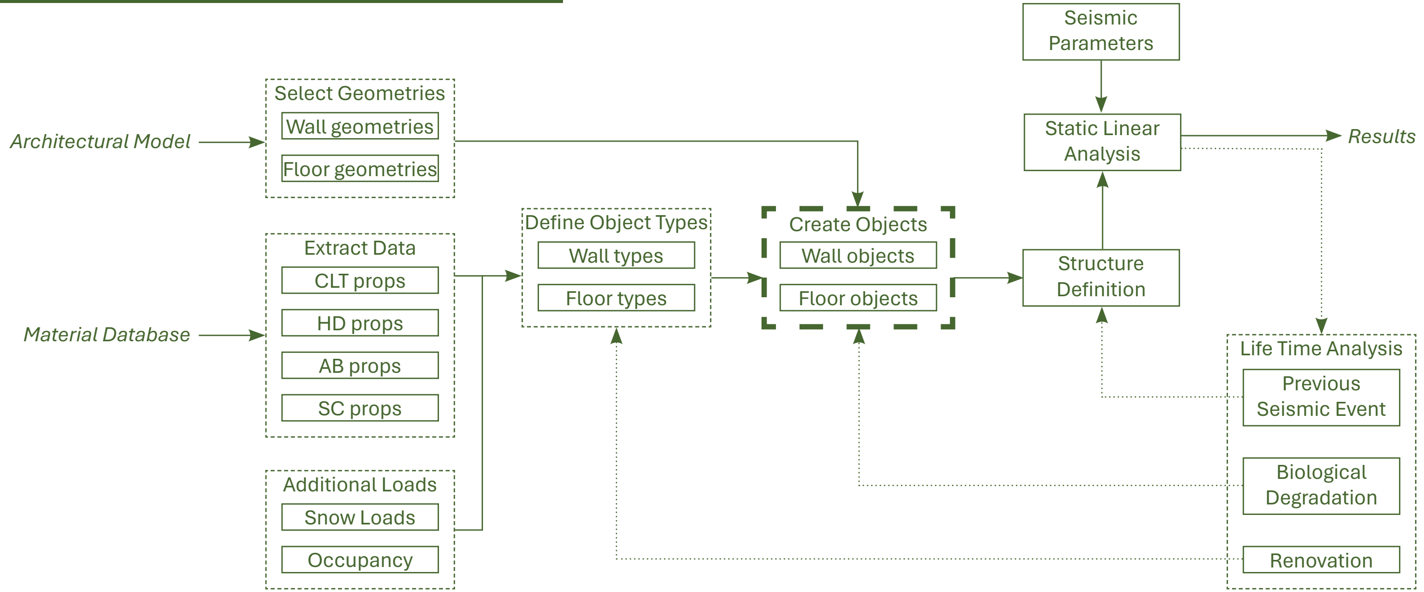


Model Generation

Wall and Floor Types

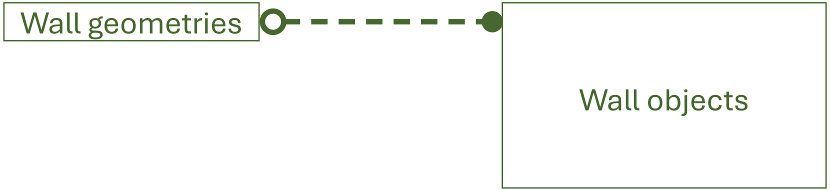


The Workflow



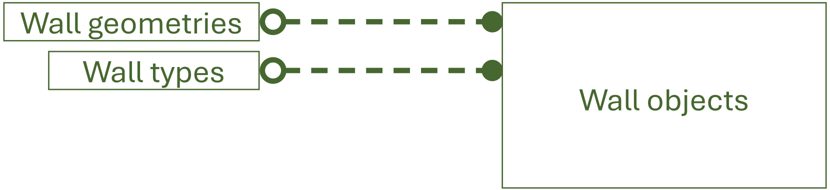
Model Generation

Wall and Floor Objects



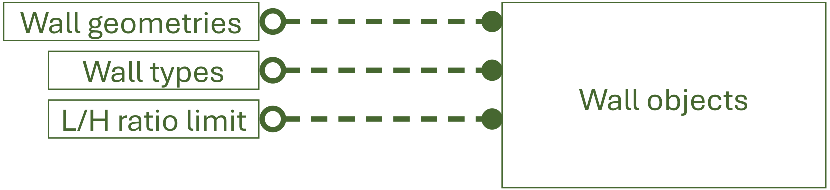
Model Generation

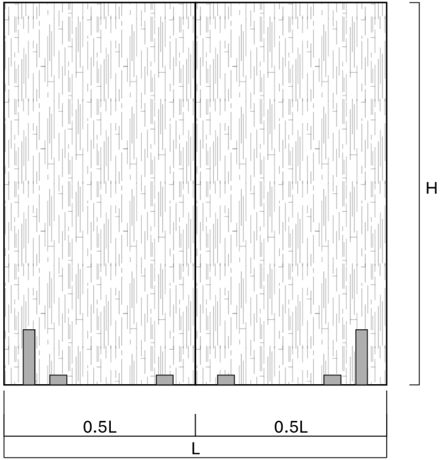
Wall and Floor Objects



Model Generation

Wall and Floor Objects



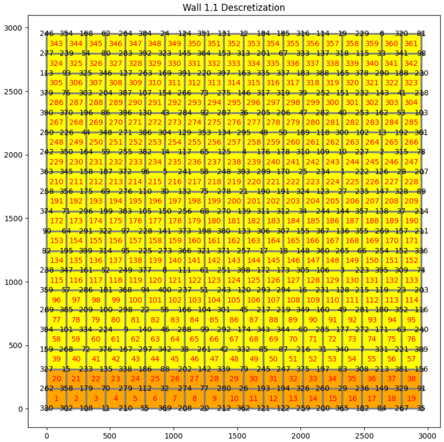


Model Generation

Wall and Floor Objects

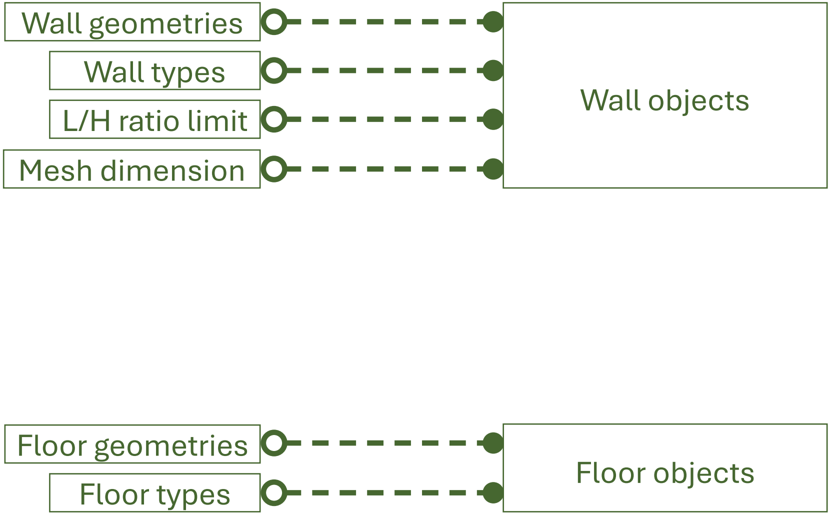
- Wall geometries
- Wall types
- L/H ratio limit
- Mesh dimension

→ Wall objects



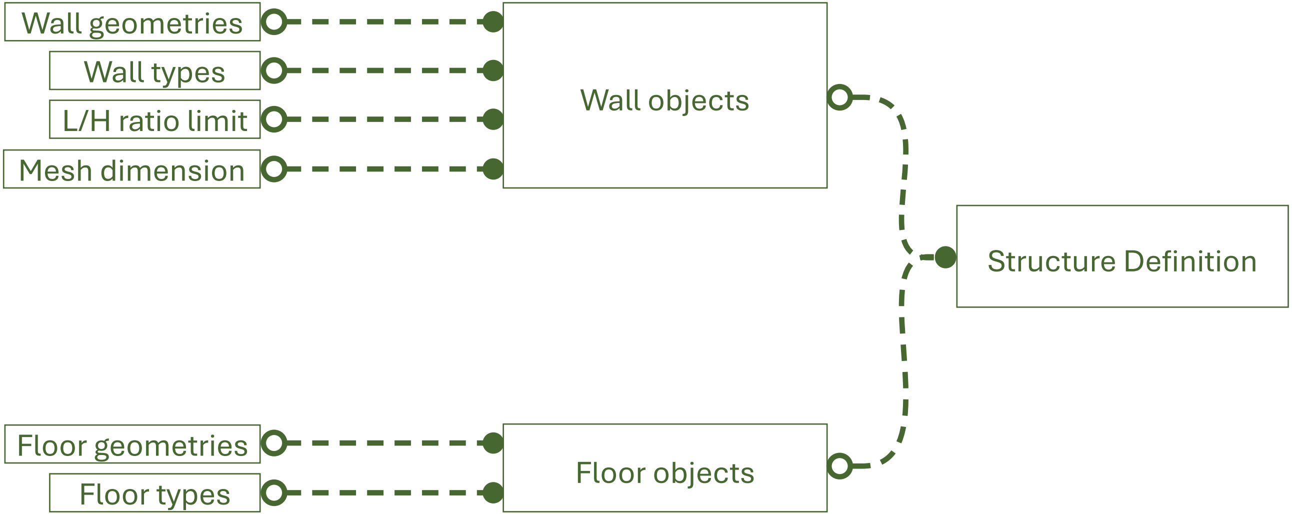
Model Generation

Wall and Floor Objects

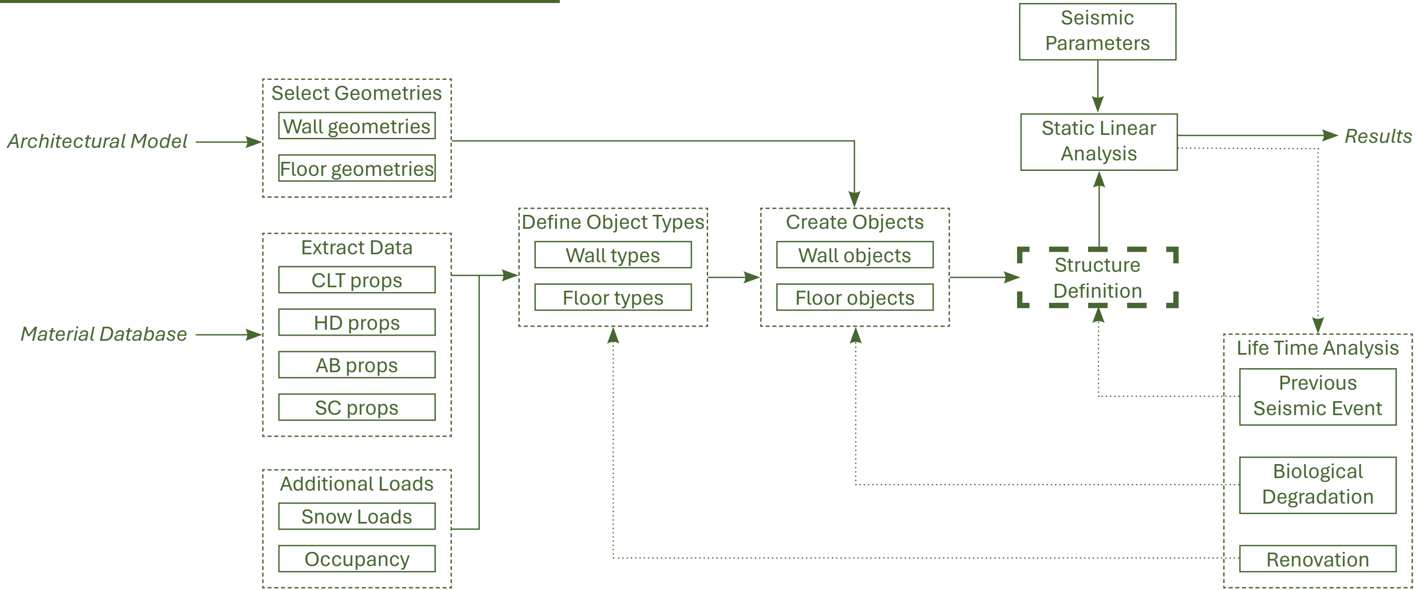


Model Generation

Wall and Floor Objects



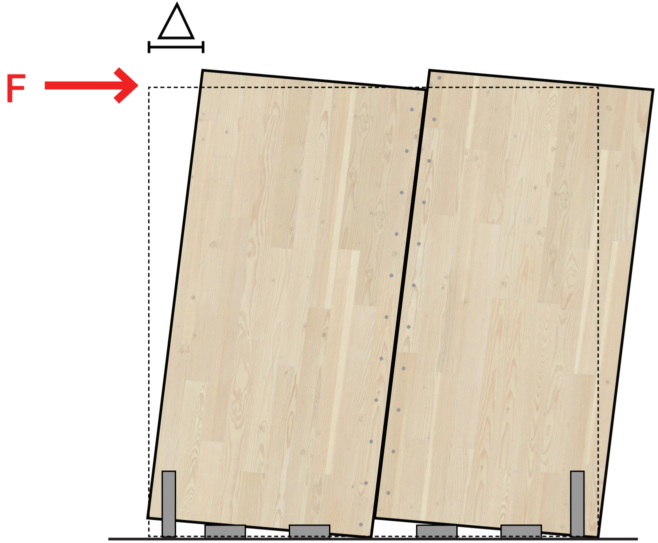
The Workflow



Model Generation

Full Structure Definition

Wall Stiffnesses

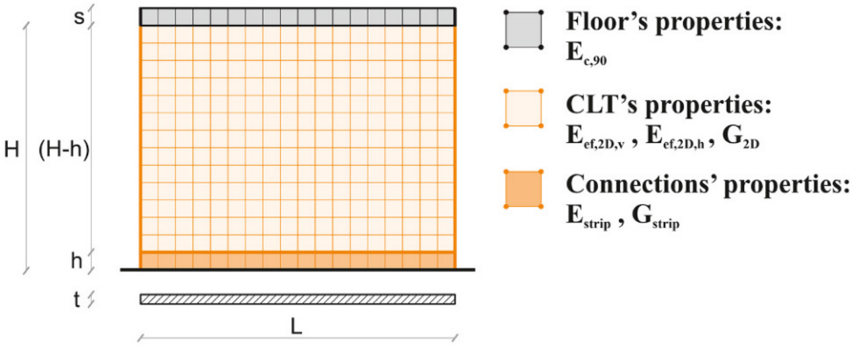


Model Generation

Full Structure Definition

Wall Stiffnesses

- Walls modelled with Rinaldi et al. 2021 strategy

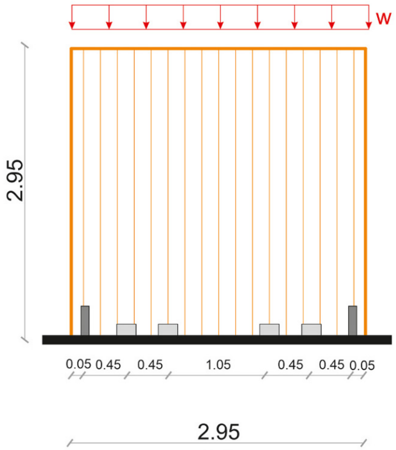


Source: Rinaldi et al. 2021

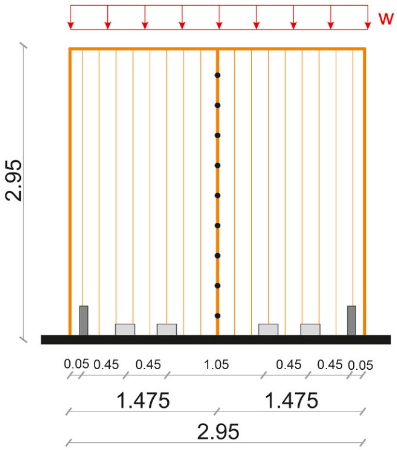
Model Generation

Full Structure Definition

Comparative Analysis



Single-panel wall configurations



Multi-panel wall configurations

Model Generation

Full Structure Definition

Comparative Analysis

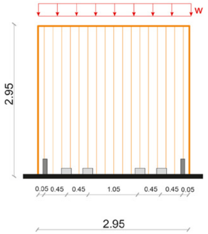
- Compare between implemented model and that of Rinaldi et al. 2021

Table – Comparative analysis results for implementation of Rinaldi modelling strategy

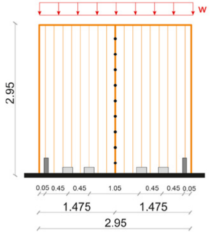
	Number of panels	E_{strip} (MPa)			G_{strip} (MPa)			Stiffness (N/mm)		
		Value	Rinaldi	% Diff.	Value	Rinaldi	% Diff.	Value	Rinaldi	% Diff.
Wall I.1	1	324.00	371.92	-12.88	3.14	3.13	+0.32	3487	3490	-0.09
Wall I.2		254.00	253.61	+0.15	6.27	6.25	+0.32	6324	5490	+15.19
Wall I.3		129.00	128.70	+0.23	6.27	6.25	+0.32	6288	4620	+36.1
Wall II.1	2		-		3.67	3.66	+0.27	4068	4360	-6.7
Wall III.1					3.11	3.10	+0.32	3501	3770	-7.14
Wall III.2					3.11	3.10	+0.32	3501	3770	-7.14
Wall III.3					3.11	3.10	+0.32	3501	3770	-7.14
Wall III.4					2.12	2.11	+0.47	2454	2670	-8.09

** mesh size of 100 mm*

Comparative analysis results



Single-panel wall configurations



Multi-panel wall configurations

Model Generation

Full Structure Definition

Comparative Analysis

- Compare between implemented model and that of Rinaldi et al. 2021
- Mesh dimension needs to be calibrated to match the values

Table – Comparative analysis results for implementation of Rinaldi modelling strategy

	Number of panels	E_{strip} (MPa) Value	Rinaldi	% Diff.	G_{strip} (MPa) Value	Rinaldi	% Diff.	Stiffness (N/mm) Value	Rinaldi	% Diff.
Wall I.1		324.00	371.92	-12.88	3.14	3.13	+0.32	3487	3490	-0.09
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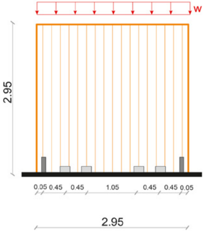
** mesh size of 100 mm*

Comparative analysis results

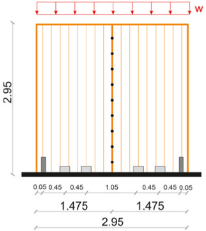


Single-panel wall configurations

Table – Comparative analysis of stiffnesses with varied mesh dimensions

Mesh dim.	No.	R.	Stiffness (N/mm) 50	%	100	%	112.5	%	125	%	150	%
		-	50	%	100	%	112.5	%	125	%	150	%
Wall I.1		3490	2888	-17.25	3487	-0.09	3159	-9.48	2825	-19.05	2367	-32.18
Wall I.2	1	5490	5316	-3.17	6324	+15.19	5780	+5.28	5216	-4.99	4428	-19.34
Wall I.3		4620	5285	+14.39	6288	+36.1	5751	+24.48	5192	+12.38	4410	-4.55
Wall II.1		4360	3376	-22.57	4068	-6.7	3688	-15.41	3299	-24.33	2767	-36.54
Wall III.1		3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.2	2	3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.3		3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.4		2670	2021	-24.31	2454	-8.09	2215	-17.04	1973	-26.01	1645	-38.39

Mesh dimension calibration



Multi-panel wall configurations

Model Generation

Full Structure Definition

Comparative Analysis

- Compare between implemented model and that of Rinaldi et al. 2021
- Mesh dimension needs to be calibrated to match the values
- Currently underestimating by 8% or less* with a mesh dimension of 100 mm

Table – Comparative analysis results for implementation of Rinaldi modelling strategy

	Number of panels	E_{strip} (MPa) Value	Rinaldi	% Diff.	G_{strip} (MPa) Value	Rinaldi	% Diff.	Stiffness (N/mm) Value	Rinaldi	% Diff.
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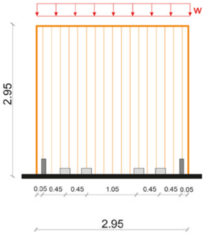
Wall III.3					3.11	3.10	+0.32	3501	3770	-7.14
Wall III.4					2.12	2.11	+0.47	2454	2670	-8.09

** mesh size of 100 mm*

Comparative analysis results



Single-panel wall configurations

Table – Comparative analysis of stiffnesses with varied mesh dimensions

Mesh dim.	No.	R.	50	%	100	%	112.5	%	125	%	150	%
		-	Stiffness (N/mm)									
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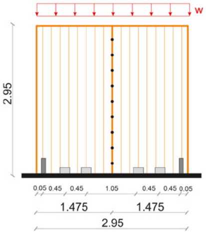
Wall II.1		4360	3376	-22.57	4068	-6.7	3688	-15.41	3299	-24.33	2767	-36.54
Wall III.1		3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.2	2	3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.3		3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.4		2670	2021	-24.31	2454	-8.09	2215	-17.04	1973	-26.01	1645	-38.39

Mesh dimension calibration



Multi-panel wall configurations

Model Generation

Full Structure Definition

Comparative Analysis

- Compare between implemented model and that of Rinaldi et al. 2021
- Mesh dimension needs to be calibrated to match the values
- Currently underestimating by 8% or less* with a mesh dimension of 100 mm
    - *Walls with 4 rather than 2 angle brackets are outliers, overestimating stiffness by up to 36%

Table – Comparative analysis results for implementation of Rinaldi modelling strategy

	Number of panels	E_{strip} (MPa) Value	Rinaldi	% Diff.	G_{strip} (MPa) Value	Rinaldi	% Diff.	Stiffness (N/mm) Value	Rinaldi	% Diff.
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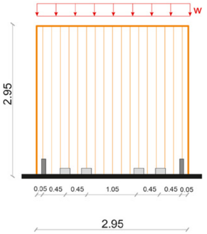
Wall III.2	2		-		3.11	3.10	+0.32	3501	3770	-7.14
Wall III.3					3.11	3.10	+0.32	3501	3770	-7.14
Wall III.4					2.12	2.11	+0.47	2454	2670	-8.09

** mesh size of 100 mm*

Comparative analysis results

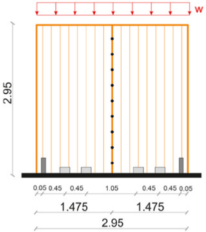


Single-panel wall configurations

Table – Comparative analysis of stiffnesses with varied mesh dimensions

Mesh dim.	No.	R. -	Stiffness (N/mm) 50	%	100	%	112.5	%	125	%	150	%
Wall I.1		3490	2888	-17.25	3487	-0.09	3159	-9.48	2825	-19.05	2367	-32.18
Wall I.2	1	5490	5316	-3.17	6324	+15.19	5780	+5.28	5216	-4.99	4428	-19.34
Wall I.3		4620	5285	+14.39	6288	+36.1	5751	+24.48	5192	+12.38	4410	-4.55
Wall II.1		4360	3376	-22.57	4068	-6.7	3688	-15.41	3299	-24.33	2767	-36.54
Wall III.1		3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.2	2	3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.3		3770	2898	-23.13	3501	-7.14	3169	-15.94	2831	-24.91	2369	-37.16
Wall III.4		2670	2021	-24.31	2454	-8.09	2215	-17.04	1973	-26.01	1645	-38.39

Mesh dimension calibration



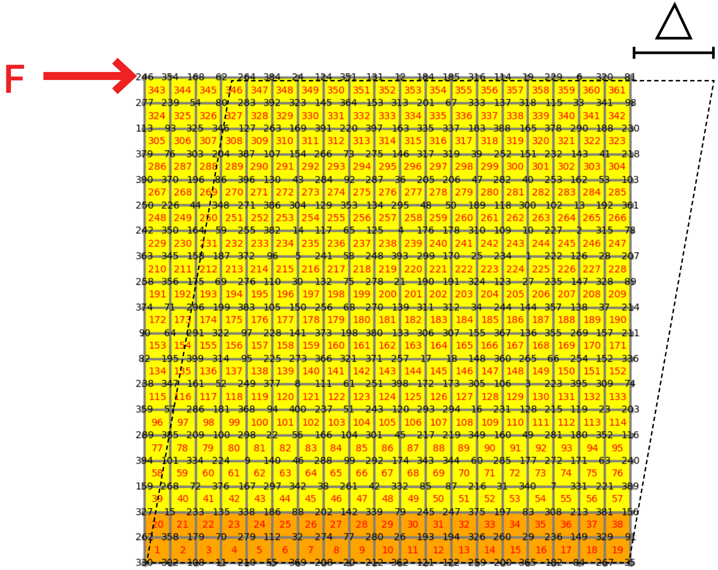
Multi-panel wall configurations

Model Generation

Full Structure Definition

Wall Stiffnesses

- Walls modelled with Rinaldi et al. 2021 strategy
- Pushover analysis



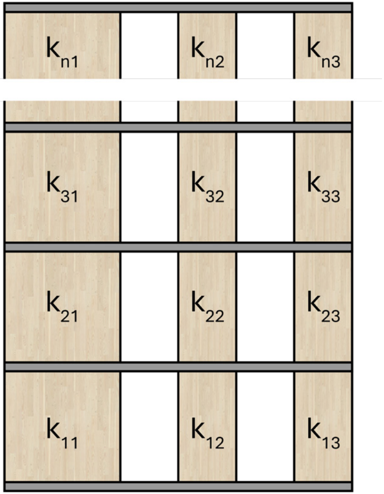
Model Generation

Full Structure Definition

Wall Stiffnesses

- Walls modelled with Rinaldi et al. 2021 strategy
- Pushover analysis

Structure Parameters



Model Generation

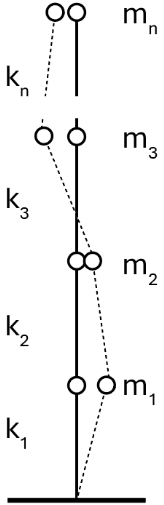
Full Structure Definition

Wall Stiffnesses

- Walls modelled with Rinaldi et al. 2021 strategy
- Pushover analysis

Structure Parameters

- Eigen analysis



Eigen model

Model Generation

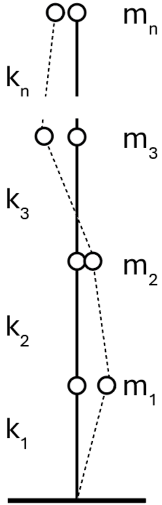
Full Structure Definition

Wall Stiffnesses

- Walls modelled with Rinaldi et al. 2021 strategy
- Pushover analysis

Structure Parameters

- Eigen analysis
- Natural building period



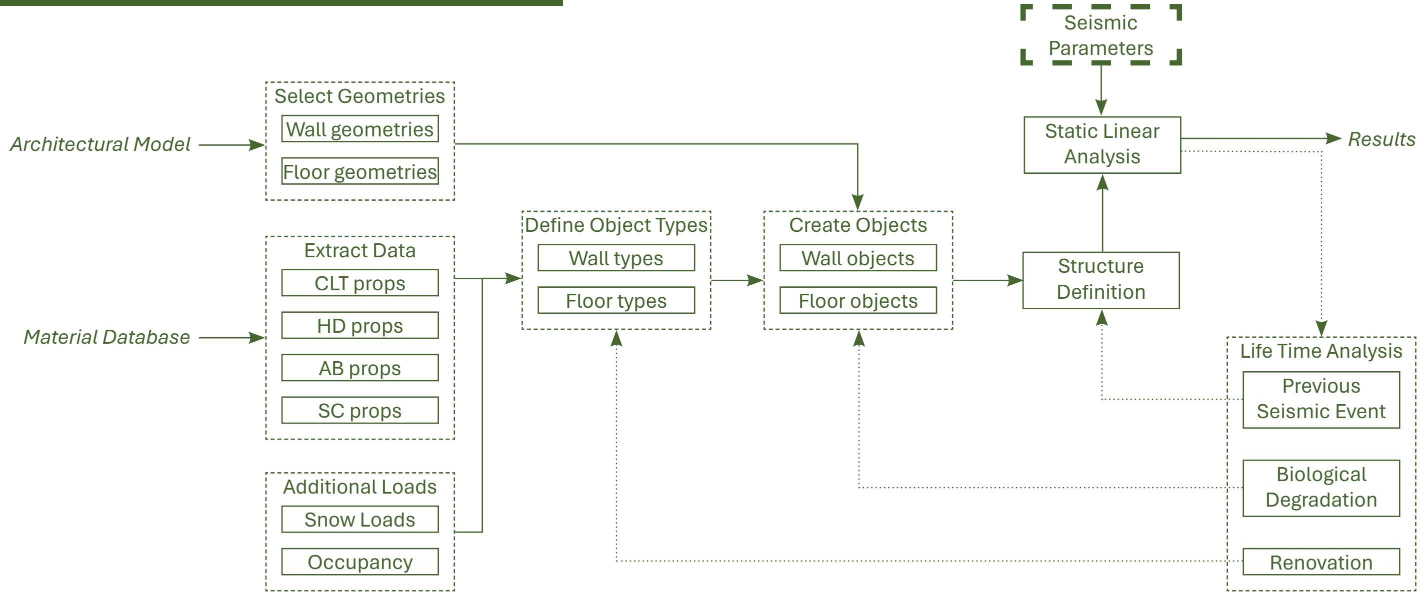
Eigen model

$$\omega = \sqrt{\frac{m}{k}} = eigen\ vector$$

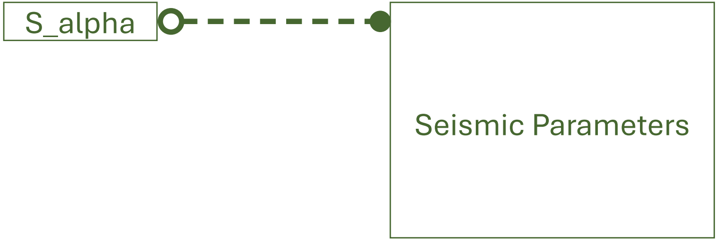
$$T = 2\pi\omega$$

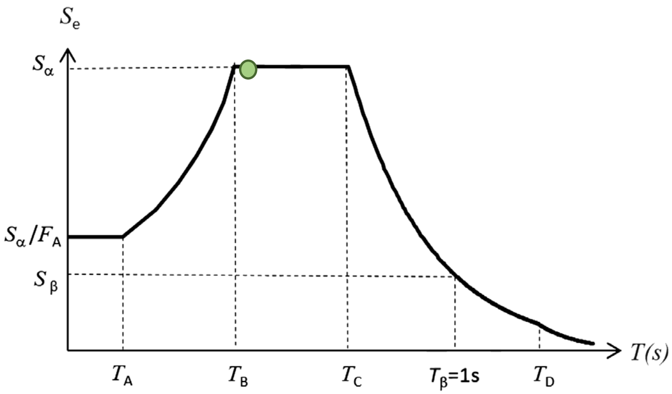
Relationship b/t eigen analysis and building period

The Workflow

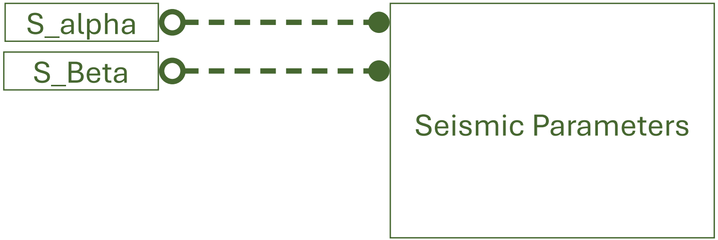


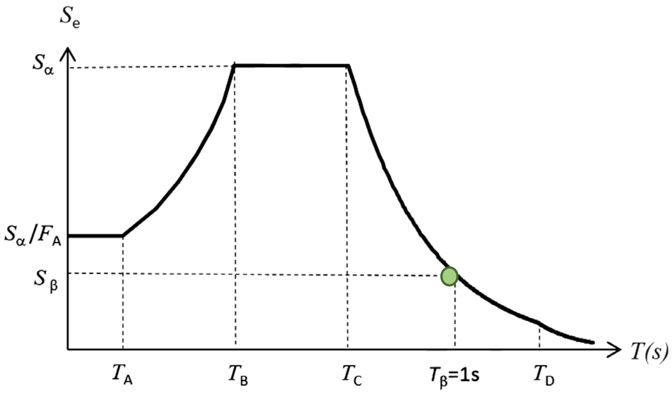
Seismic Parameters



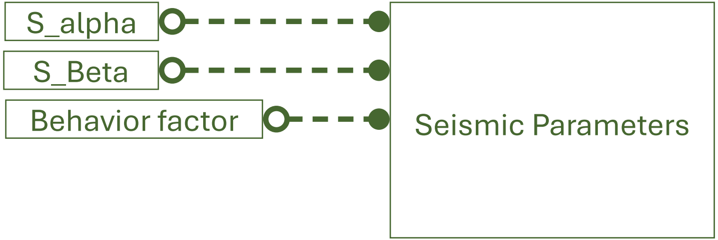


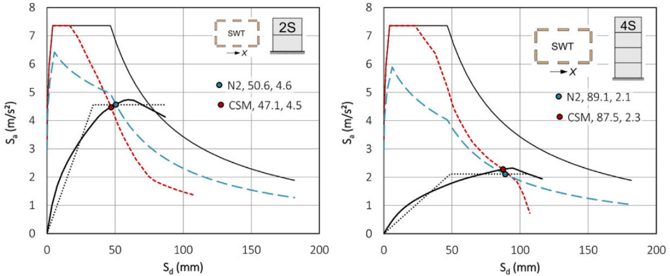
Seismic Parameters





Seismic Parameters





Behavior factor q = 3.0
Source: Hummel and Seim, 2019

Seismic Parameters

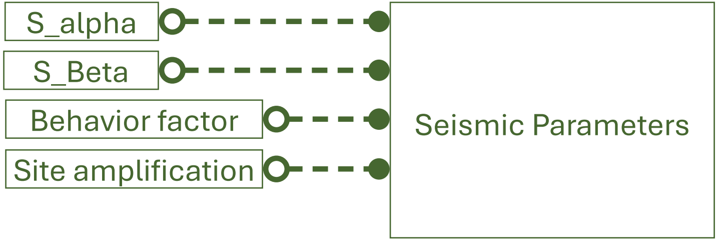


Table 5.4 — Site amplification factors F_α and F_β for the standard site categories of Table 5.1

Site category	F_α		F_β	
	H_{800} and $v_{s,H}$ available	Default value	H_{800} and $v_{s,H}$ available	Default value
A	1,0	1,0	1,0	1,0
B	$\left(\frac{v_{s,H}}{800}\right)^{-0,40\, r_\alpha}$	$1,3\ (1 - 0,1\ S_{\alpha,RP}/g)$	$\left(\frac{v_{s,H}}{800}\right)^{-0,70\, r_\beta}$	$1,6\ (1 - 0,2\ S_{\beta,RP}/g)$
C		$1,6\ (1 - 0,2\ S_{\alpha,RP}/g)$		$2,3\ (1 - 0,3\ S_{\beta,RP}/g)$
D		$1,8\ (1 - 0,3\ S_{\alpha,RP}/g$		$3,2\ (1 - S_{\beta,RP}/g)$
E	$\left(\frac{v_{s,H}}{800}\right)^{-0,40\, r_\alpha \frac{H}{30}\left(4-\frac{H}{10}\right)}$	$2,2\ (1 - 0,5\ S_{\alpha,RP}/g)$	$\left(\frac{v_{s,H}}{800}\right)^{-0,70\, r_\beta \frac{H}{30}}$	$3,2\ (1 - S_{\beta,RP}/g)$
F	$0,90\ \left(\frac{v_{s,H}}{800}\right)^{-0,40\, r_\alpha}$	$1,7\ (1 - 0,3\ S_{\alpha,RP}/g)$	$1,25 \cdot \left(\frac{v_{s,H}}{800}\right)^{-0,70\, r_\beta}$	$4,0\ (1 - S_{\beta,RP}/g)$
	with $r_\alpha = 1 - \frac{S_{\alpha,RP}/g}{v_{s,H}/150}$ and $r_\beta = 1 - \frac{S_{\beta,RP}/g}{v_{s,H}/150}$			

Site amplification factors per EN 1998

Seismic Parameters

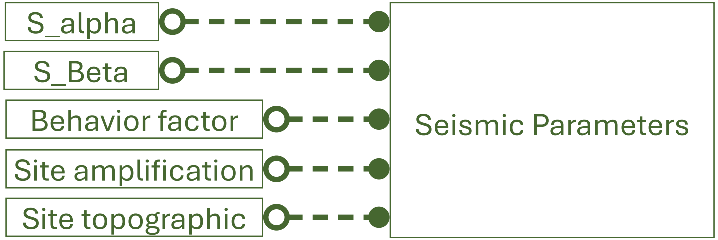
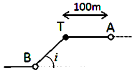
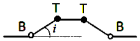
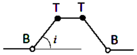
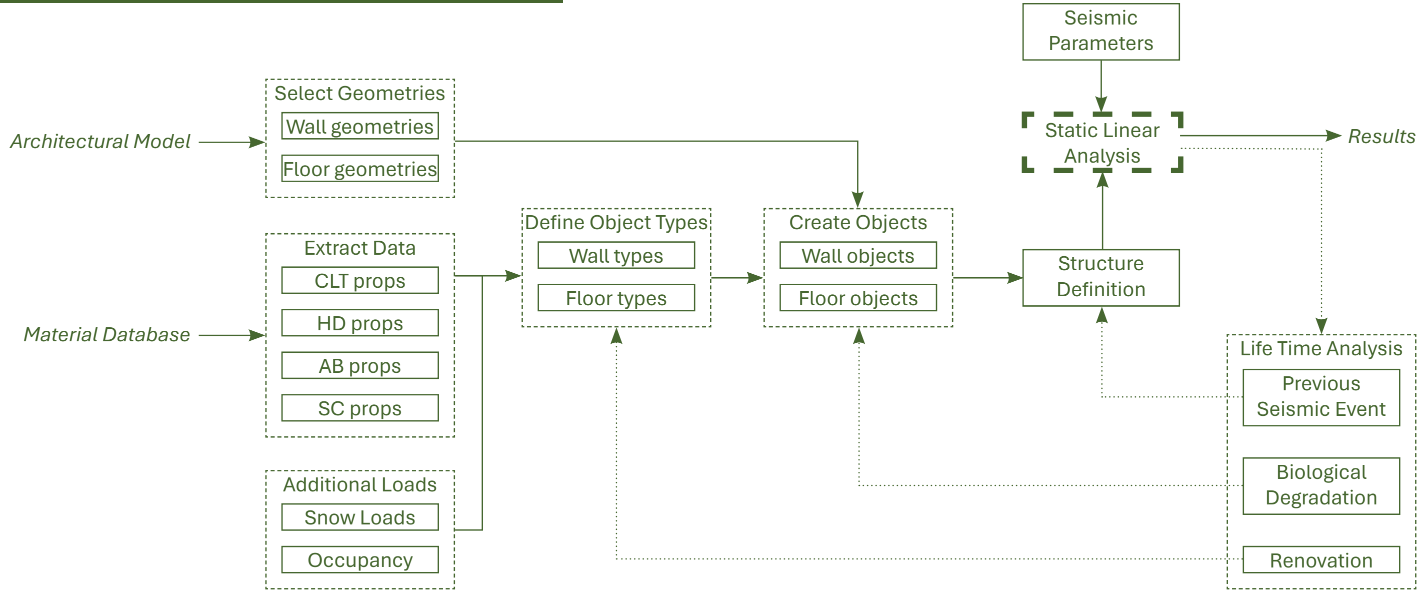


Table 5.5 — Topography amplification factors for simple topographic irregularities

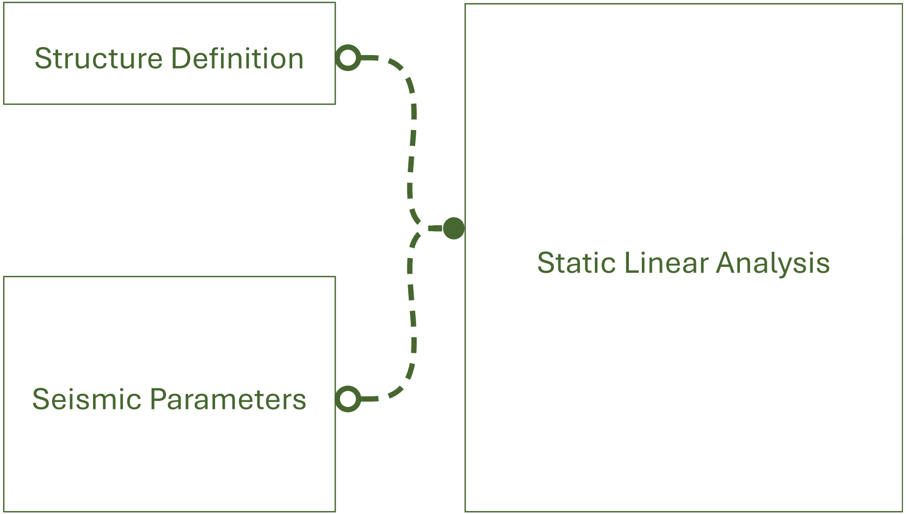
Topography description	F_T	Simplified sketch*
Flat ground surface, slopes and isolated ridges with average slope angle $i < 15°$ or height < 30 m	1,0	
Slopes with average slope angle $i > 15°$	1,2	
Ridges with width at the top much smaller than at the base and average slope angle $15° < i < 30°$	1,2	
Ridges with width at the top much smaller than at the base and average slope angle $i > 30°$	1,4	

Topographic amplification factors per EN 1998

The Workflow



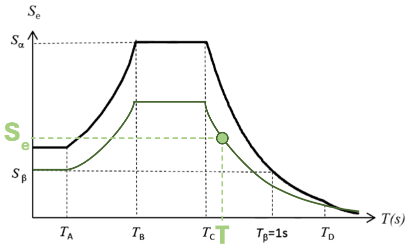
Static Linear Analysis



Static Linear Analysis

Structure Definition

Seismic Parameters

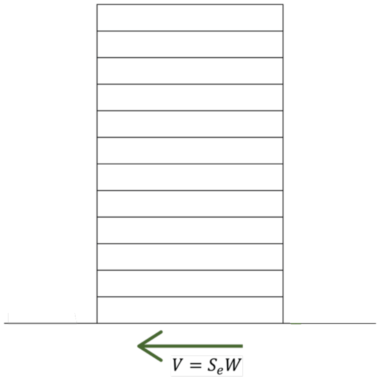


Building Period

Static Linear Analysis

Structure Definition

Seismic Parameters



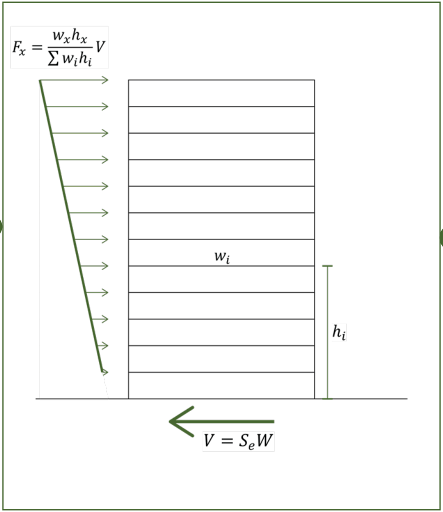
Building Period

Base Shear

Static Linear Analysis

Structure Definition

Seismic Parameters



Building Period

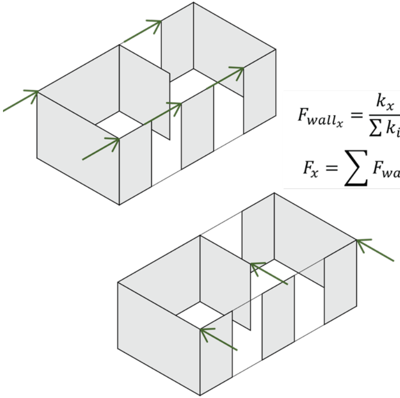
Base Shear

Story forces

Static Linear Analysis

Structure Definition

Seismic Parameters



$$F_{wall_x} = \frac{k_x}{\sum k_i} F_x$$

$$F_x = \sum F_{wall_i}$$

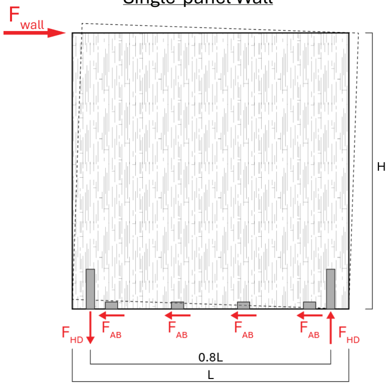
- Building Period
- Base Shear
- Story forces
- Wall forces

Static Linear Analysis

Structure Definition

Seismic Parameters

Single-panel Wall



Building Period

Base Shear

Story forces

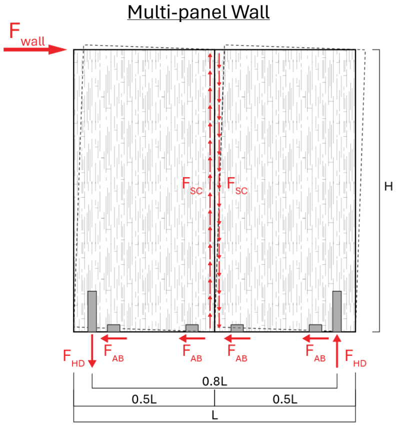
Wall forces

Forces in connections

Static Linear Analysis

Structure Definition

Seismic Parameters



Building Period

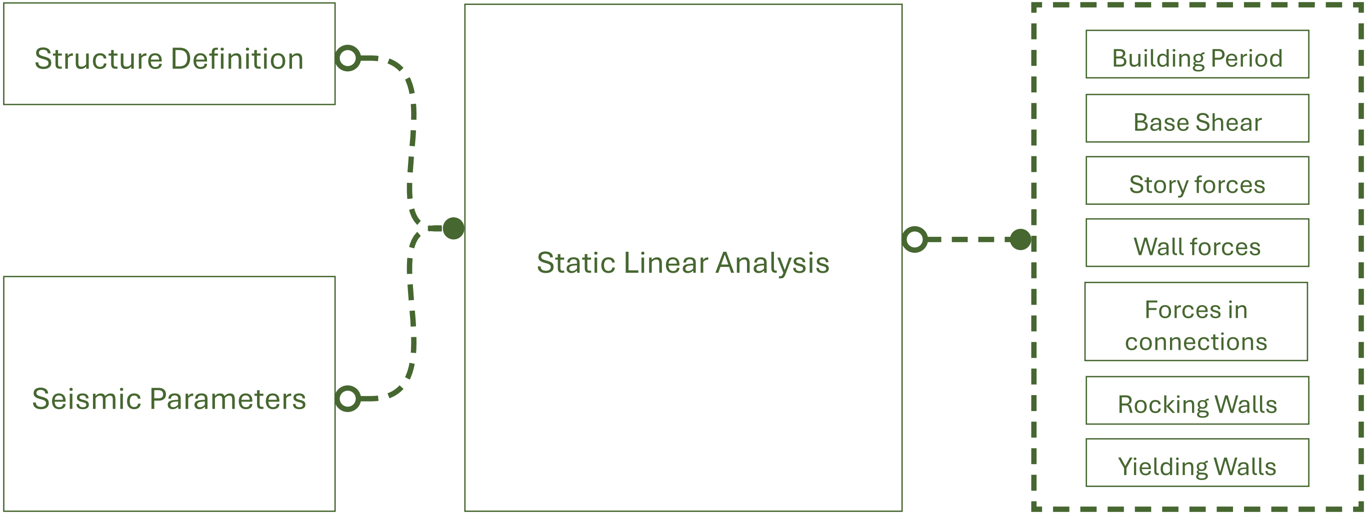
Base Shear

Story forces

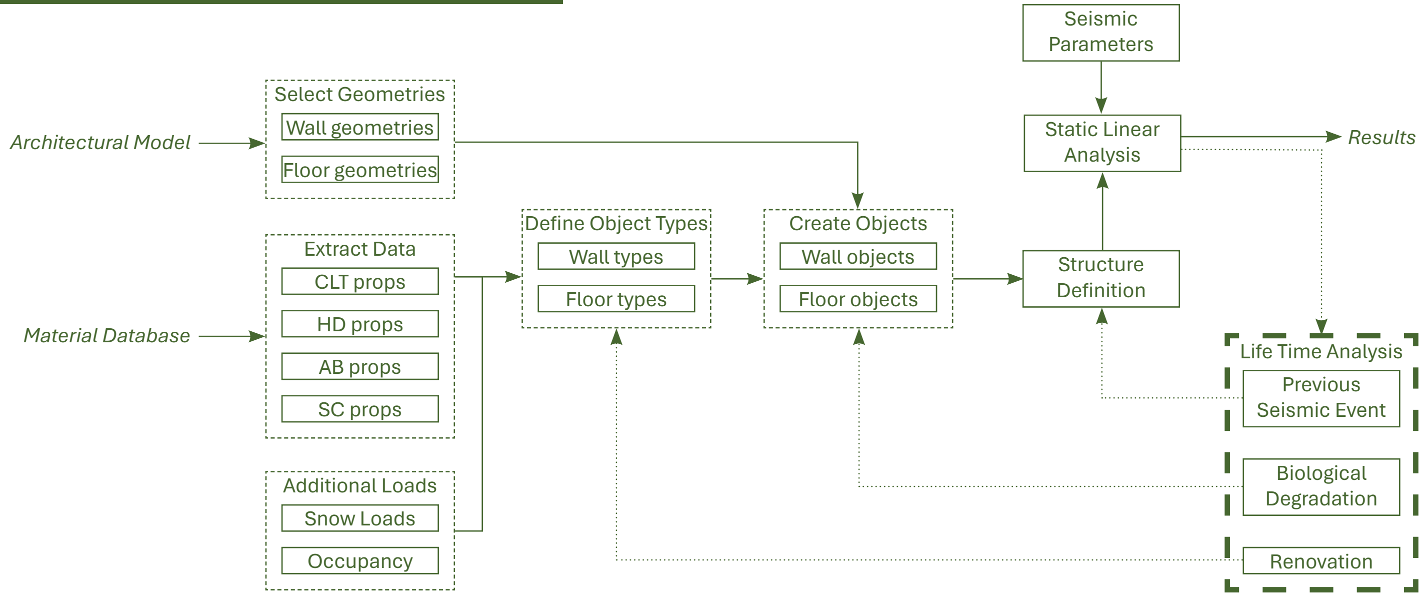
Wall forces

Forces in connections

Static Linear Analysis



The Workflow



Life Time Analysis

Previous Seismic Event

Structure Definition
(post earthquake)

Life Time Analysis

Previous Seismic Event

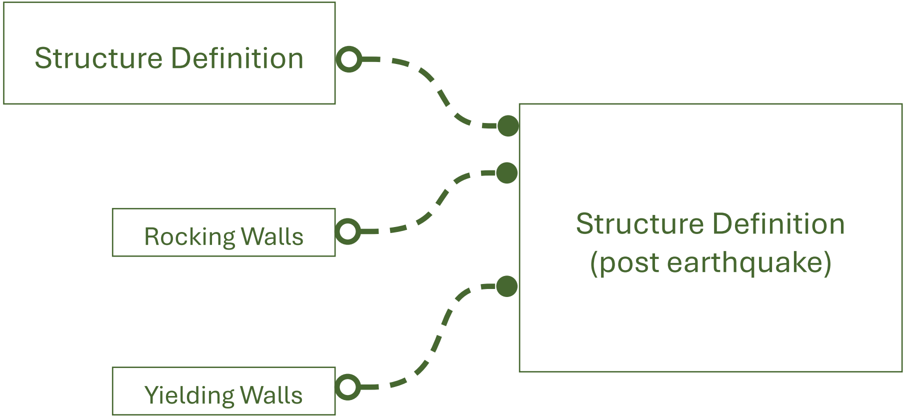
Structure Definition

Structure Definition (post earthquake)

- Building Period
- Base Shear
- Story forces
- Wall forces
- Forces in connections
- Rocking Walls
- Yielding Walls

Life Time Analysis

Previous Seismic Event



- Building Period
- Base Shear
- Story forces
- Wall forces
- Forces in connections
- Rocking Walls
- Yielding Walls

Life Time Analysis

Previous Seismic Event

Structure Definition

Rocking Walls

Reduction factor for rocking walls

Yielding Walls

Structure Definition (post earthquake)

Life Time Analysis

Previous Seismic Event

Structure Definition

Rocking Walls

Reduction factor for rocking walls

Yielding Walls

Reduction factor for yielding walls

Structure Definition (post earthquake)

Life Time Analysis

Previous Seismic Event

Structure Definition

Rocking Walls

Reduction factor for rocking walls

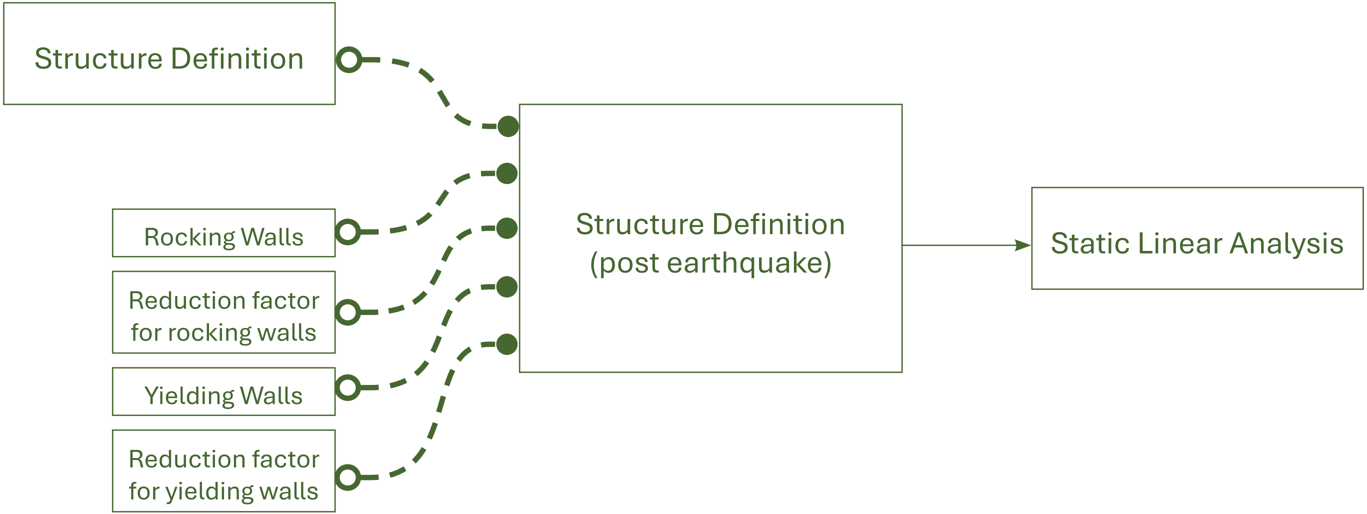
Yielding Walls

Reduction factor for yielding walls

Structure Definition (post earthquake)

Life Time Analysis

Previous Seismic Event



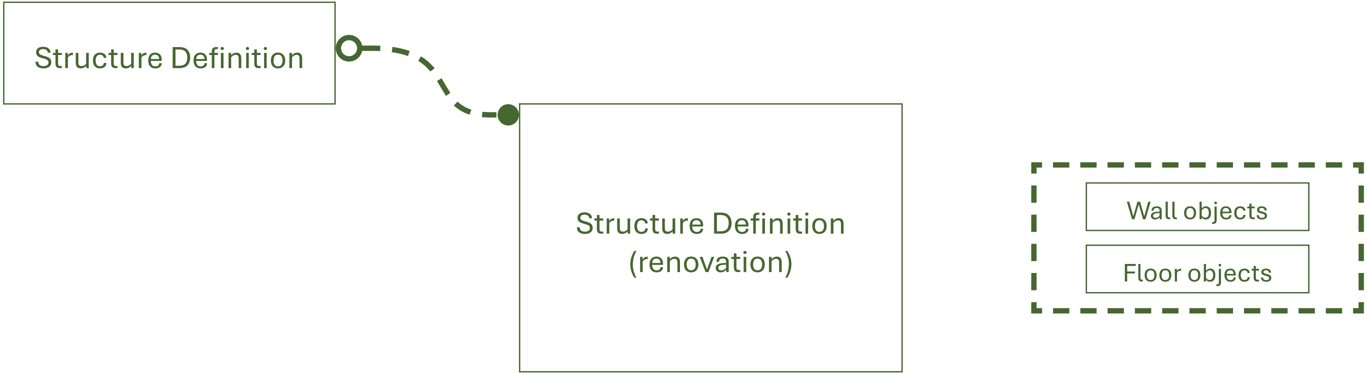
Life Time Analysis

Renovation

Structure Definition
(renovation)

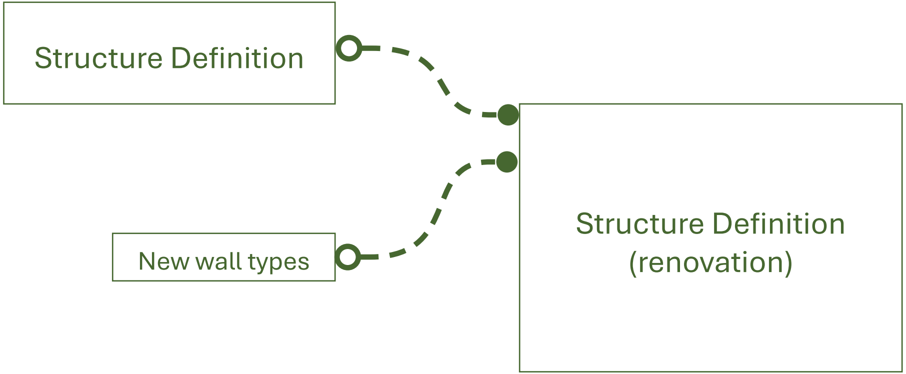
Life Time Analysis

Renovation



Life Time Analysis

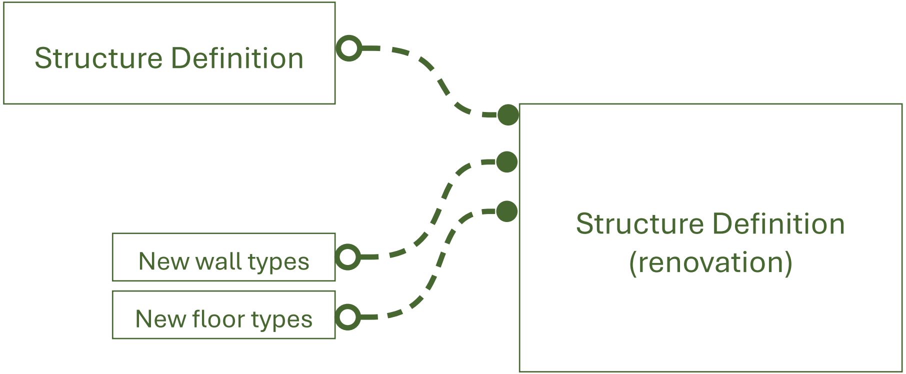
Renovation



Facade renovation

Life Time Analysis

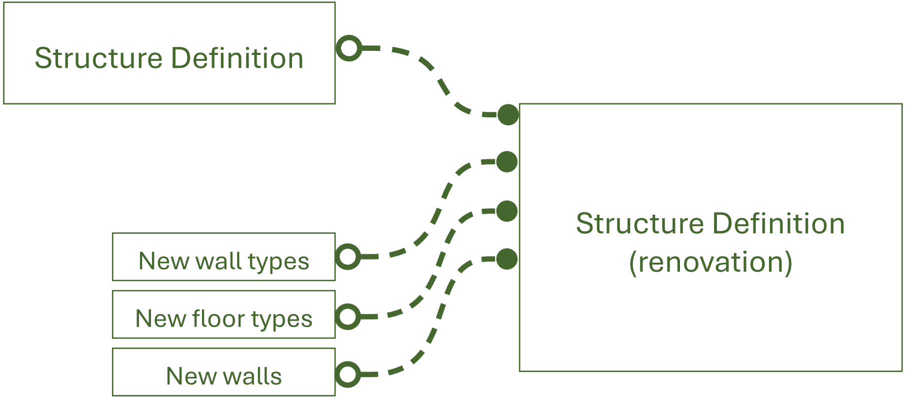
Renovation

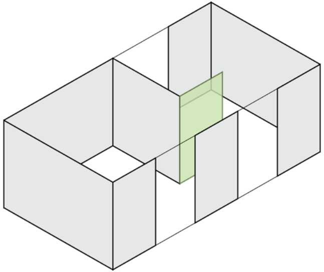


Change in occupancy

Life Time Analysis

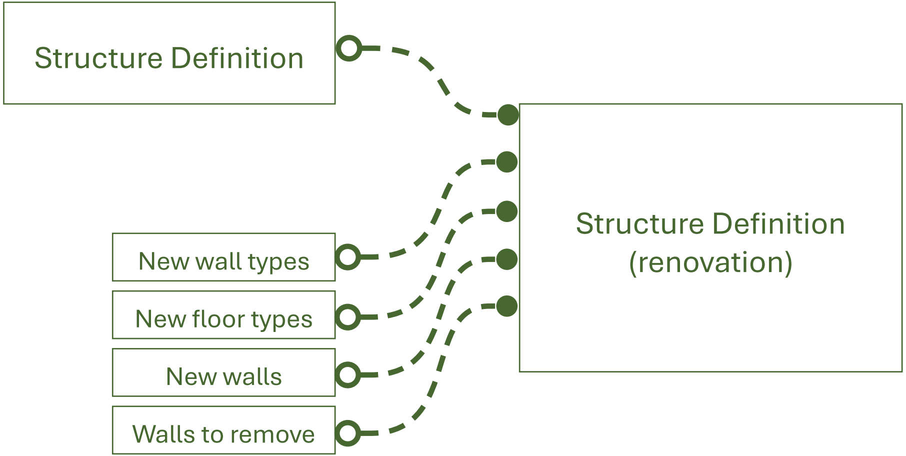
Renovation

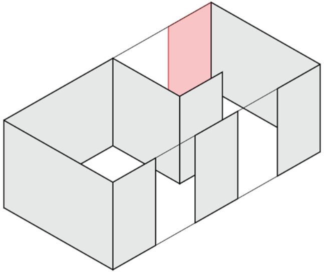




Life Time Analysis

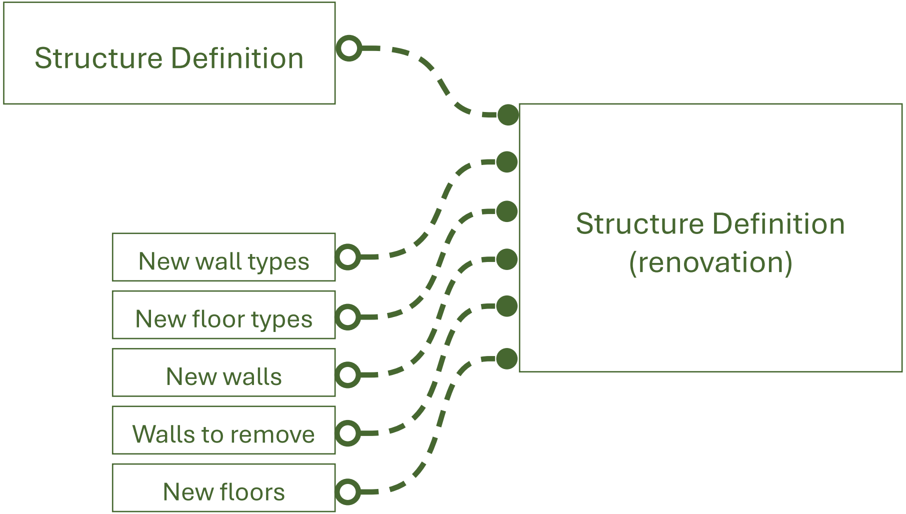
Renovation

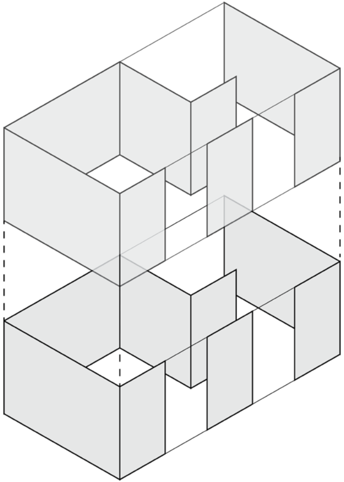




Life Time Analysis

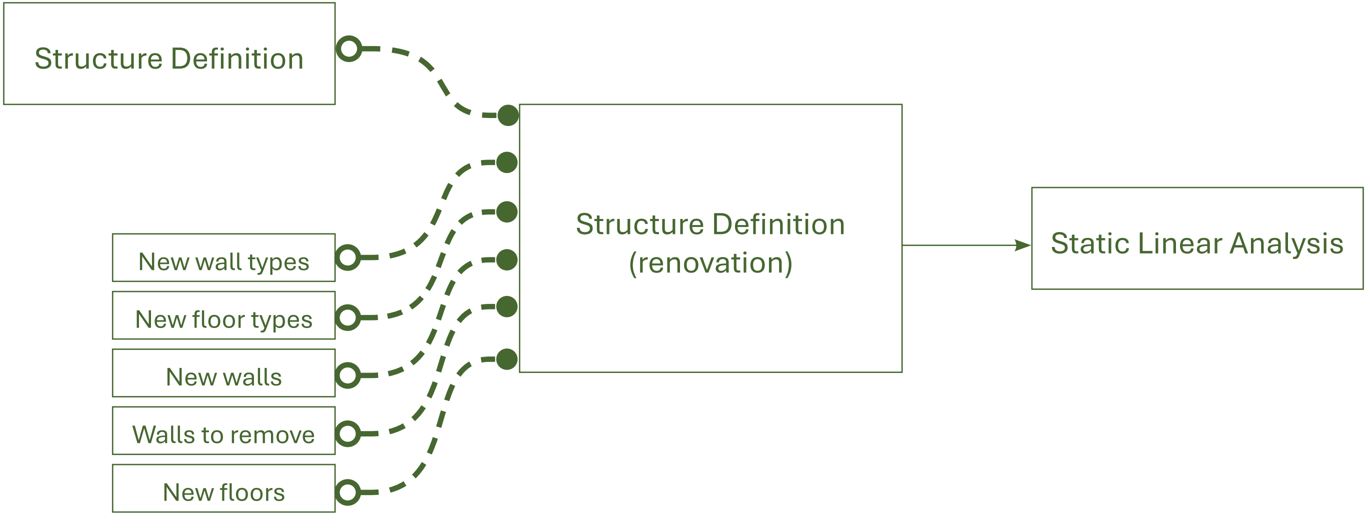
Renovation





Life Time Analysis

Renovation



Life Time Analysis

Biological Degradation - Walls over time

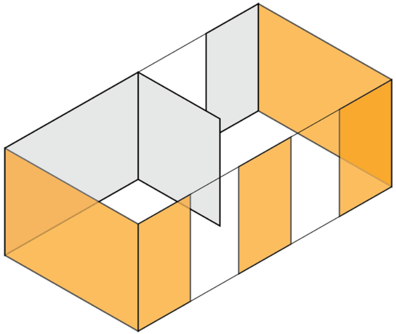
Biological Degradation
of walls over time

Life Time Analysis

Biological Degradation - Walls over time

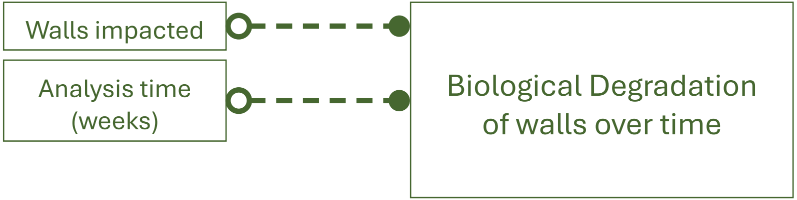
Walls impacted

Biological Degradation of walls over time



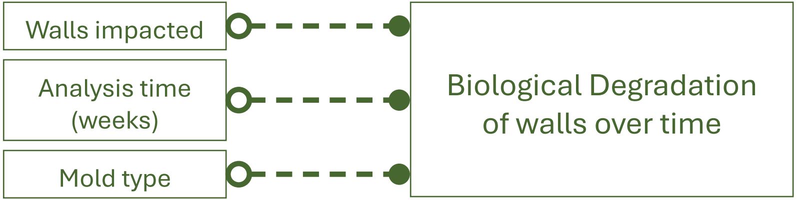
Life Time Analysis

Biological Degradation - Walls over time



Life Time Analysis

Biological Degradation - Walls over time



<u>Gloeophyllum trabeum</u>

$$F_{dbs_{DF}} = \sqrt{-16(time) + 1891.2}$$

$$F_{dbs_{NS}} = -0.31(time) + 32.3$$

$$F_{dbs_{SPF}} = -0.26(time) + 37.1$$

<u>Rhodonia placenta</u>

$$F_{dbs_{DF}} = -0.58(time) + 45.2$$

$$F_{dbs_{NS}} = -0.23(time) + 32.7$$

$$F_{dbs_{SPF}} = -0.32(time) + 33.6$$

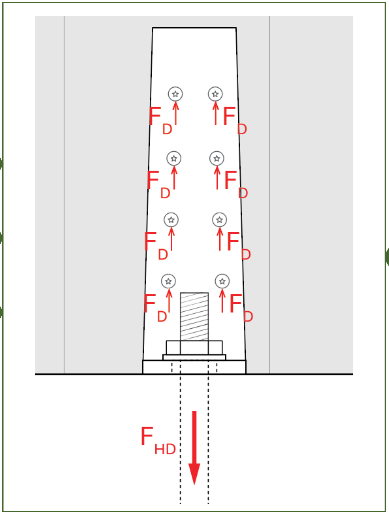
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



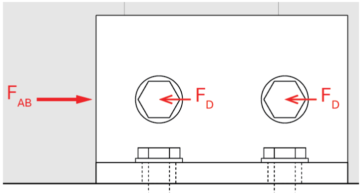
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



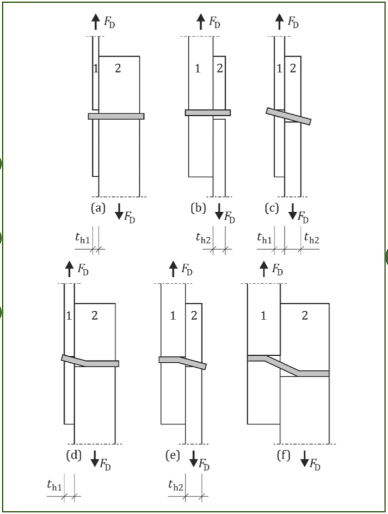
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



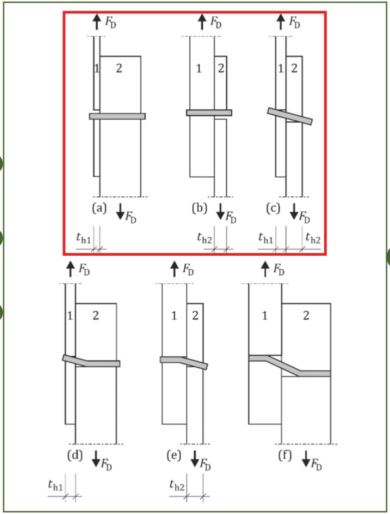
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



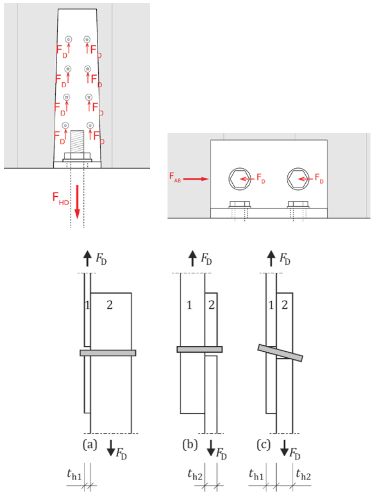
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



Rocking Walls

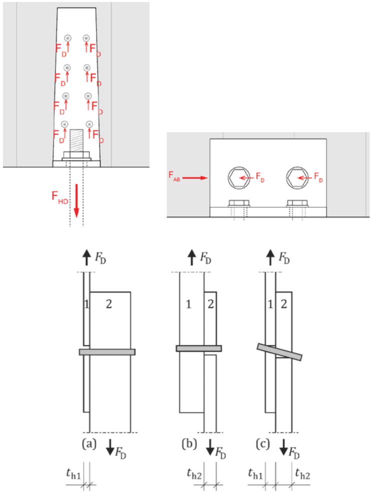
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



Rocking Walls

Yielding Walls

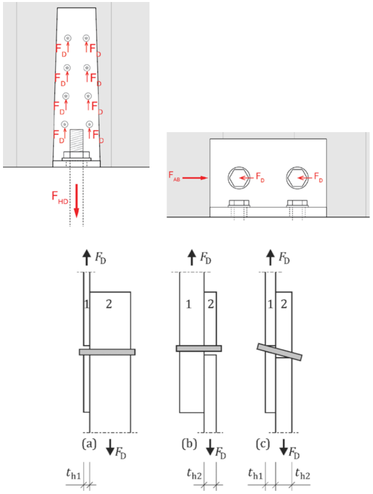
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



Rocking Walls

Yielding Walls

Time where reduced embedment strength causes early yield

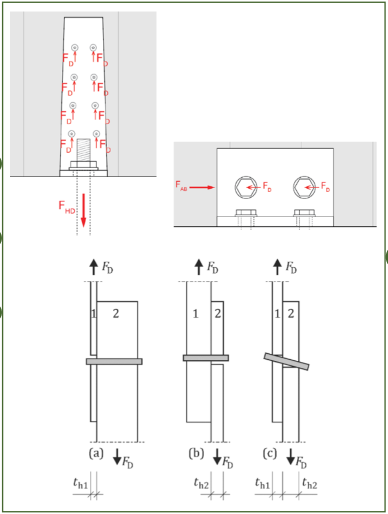
Life Time Analysis

Biological Degradation - Walls over time

Walls impacted

Analysis time (weeks)

Mold type



Rocking Walls

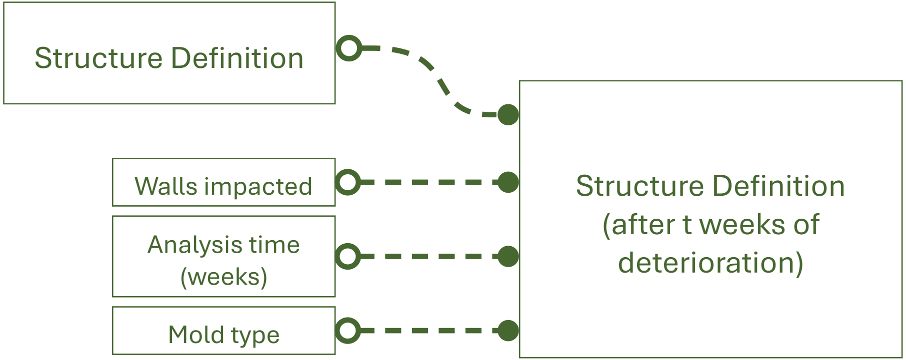
Yielding Walls

Time where reduced embedment strength causes early yield

Time where reduced embedment strength controls

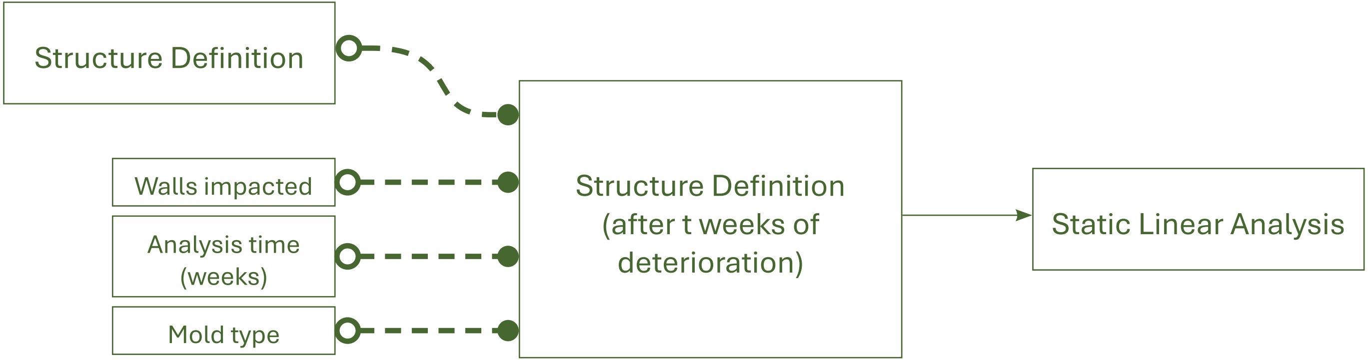
Life Time Analysis

Biological Degradation - Structure at time t

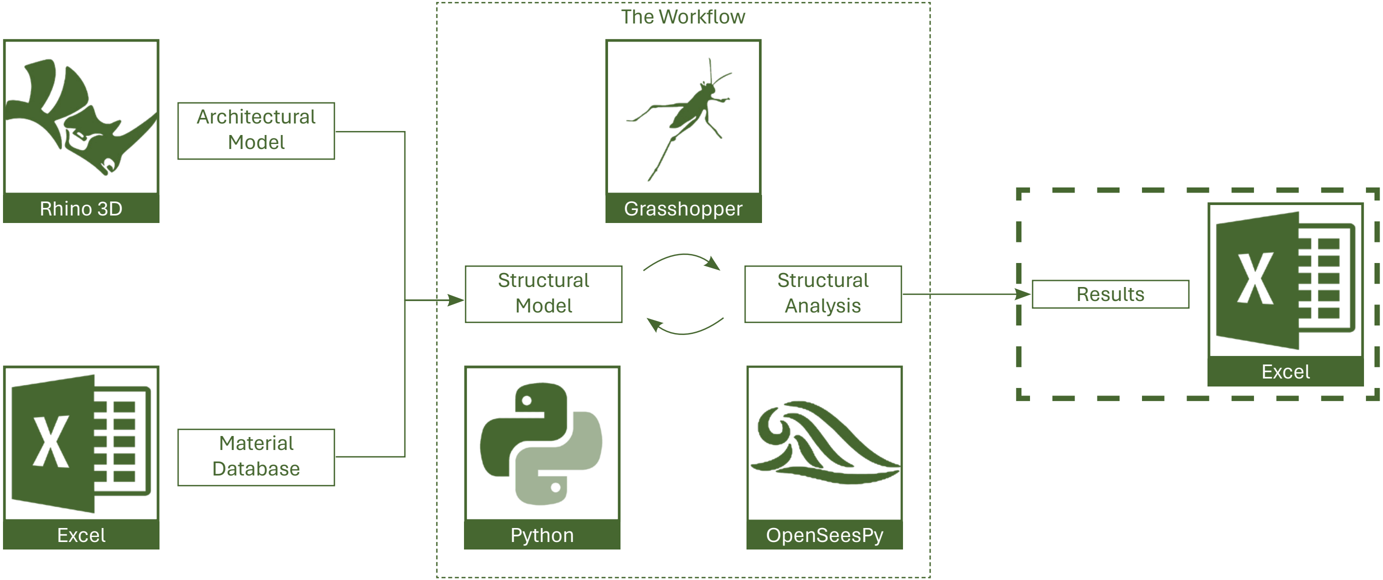


Life Time Analysis

Biological Degradation - Structure at time t



Programs and Workflow



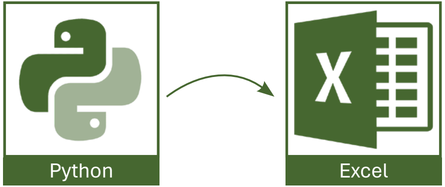
Results

Automatically Exported to Excel for Post-Processing

Python

Results

Automatically Exported to Excel for Post-Processing



Results

Automatically Exported to Excel for Post-Processing

Original Structure

Results

Automatically Exported to Excel for Post-Processing

Original Structure

Structure data

Results

Automatically Exported to Excel for Post-Processing

Original Structure

Structure data

Wall types

Results

Automatically Exported to Excel for Post-Processing

Original Structure

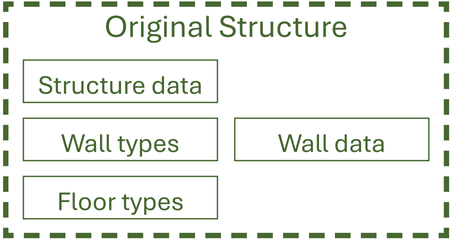
Structure data

Wall types

Wall data

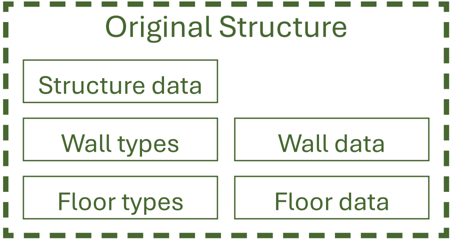
Results

Automatically Exported to Excel for Post-Processing



Results

Automatically Exported to Excel for Post-Processing



Results

Automatically Exported to Excel for Post-Processing

Original Structure
- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Earthquake Structure
- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Results

Automatically Exported to Excel for Post-Processing

Original Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Earthquake Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Future Renovation Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Results

Automatically Exported to Excel for Post-Processing

Original Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Earthquake Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Future Renovation Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Bio Degradation Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Results

Automatically Exported to Excel for Post-Processing

Original Structure
- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Earthquake Structure
- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Future Renovation Structure
- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Bio Degradation Structure
- Structure data
- Wall vs time
- Wall types
- Wall data
- Floor types
- Floor data

Results

Automatically Exported to Excel for Post-Processing

Original Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Earthquake Structure

- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Future Renovation Structure

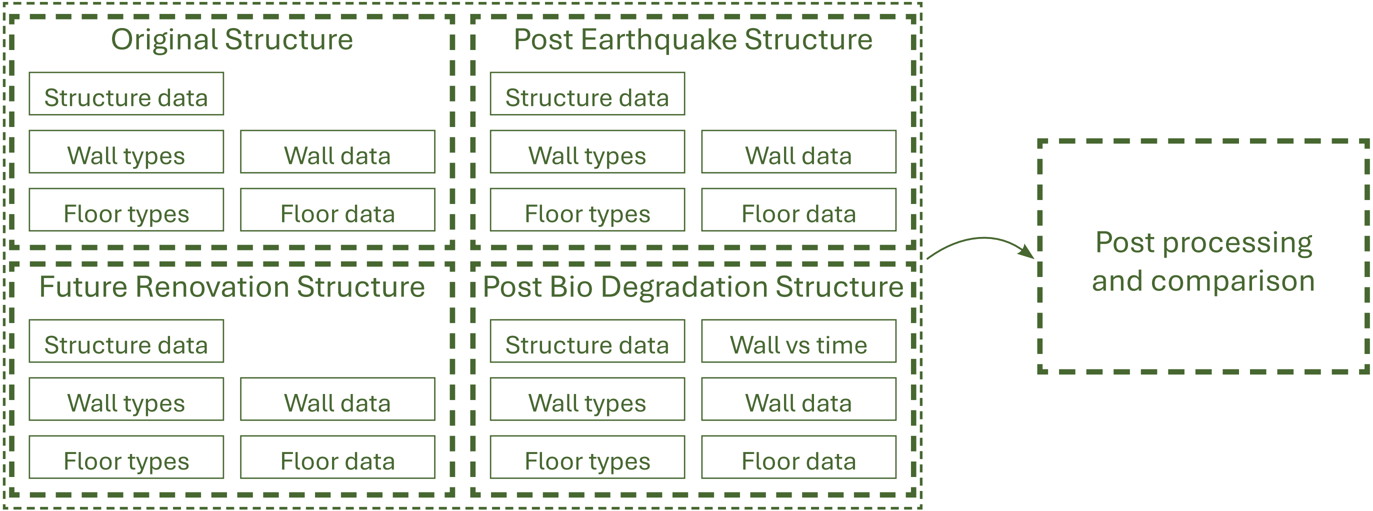
- Structure data
- Wall types
- Wall data
- Floor types
- Floor data

Post Bio Degradation Structure

- Structure data
- Wall vs time
- Wall types
- Wall data
- Floor types
- Floor data

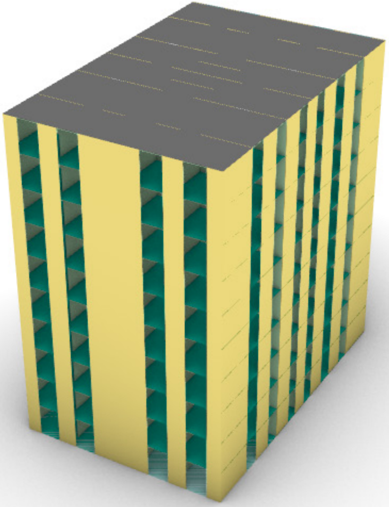
Results

Automatically Exported to Excel for Post-Processing

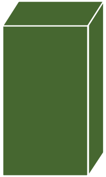


Case Study

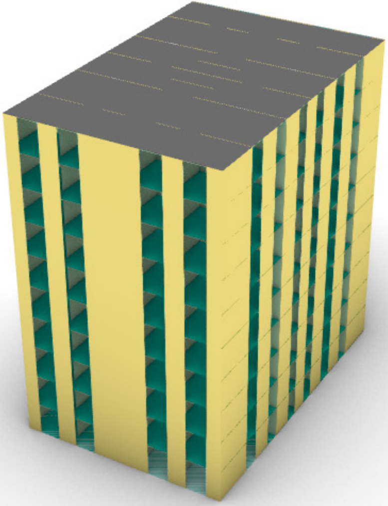
Case Study Parameters



Case Study Parameters



Rectilinear



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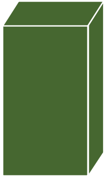
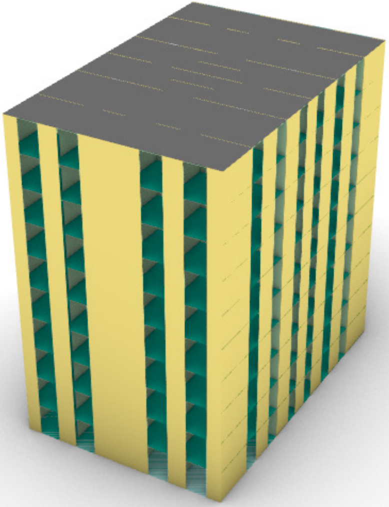
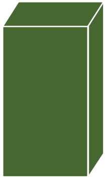


Rectilinear

Residential

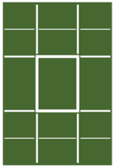


Case Study Parameters

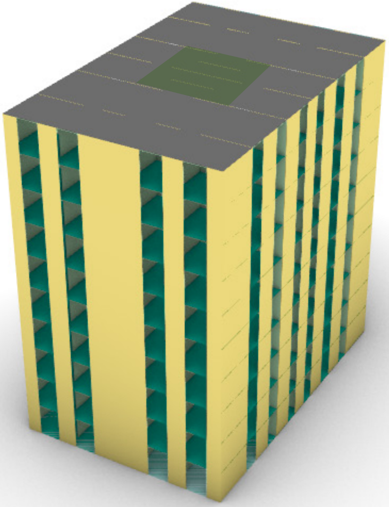


Rectilinear

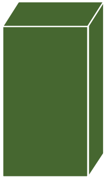
Residential



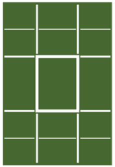
Central Core

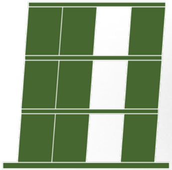


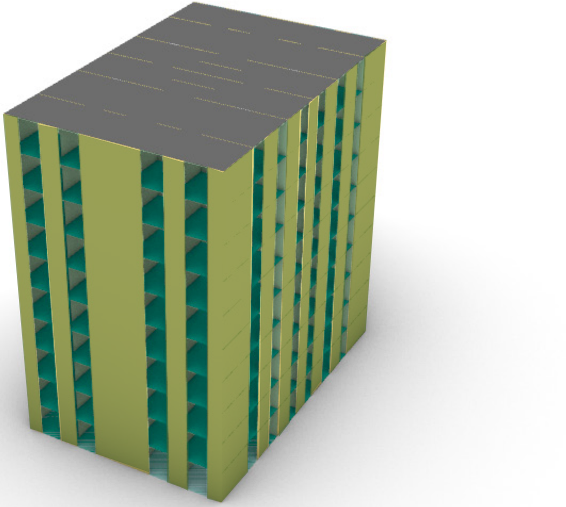
Case Study Parameters


Rectilinear

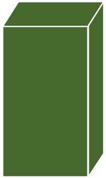

Residential


Central Core


Shear Walls

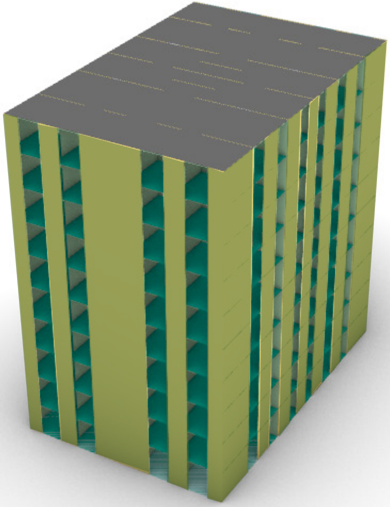


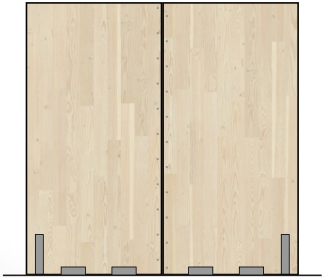
Case Study Parameters

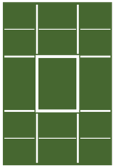


Rectilinear

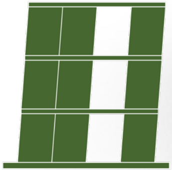
Residential



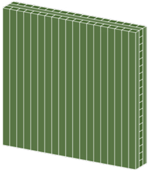




Central Core

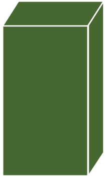


Shear Walls

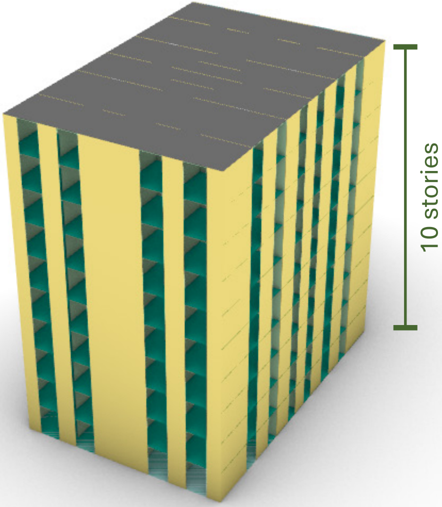


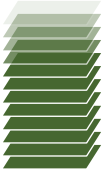
CLT Walls

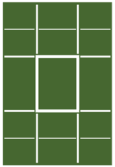
Case Study Parameters

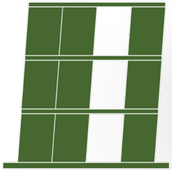

Rectilinear

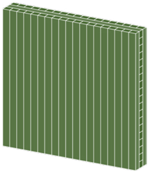

Residential




8+ stories


Central Core


Shear Walls


CLT Walls

Case Study Parameters

Europe Region

Case Study Parameters

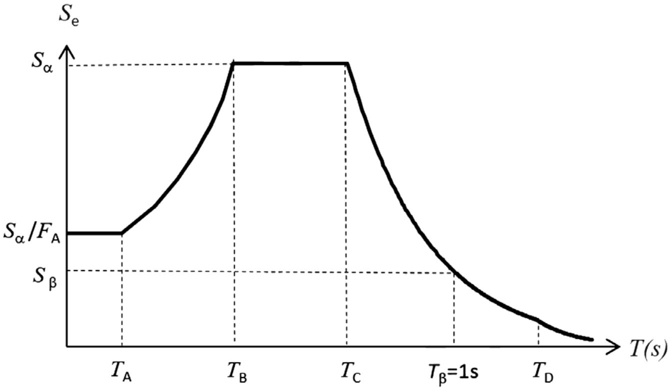
Europe Region

Case Study Parameters

Europe Region

Case Study Parameters

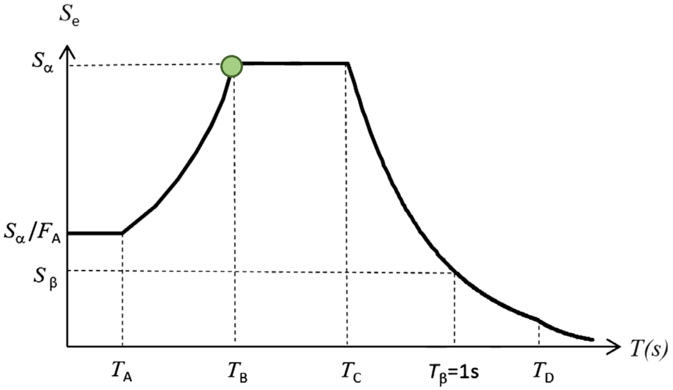
Europe Region



Case Study Parameters

Europe Region

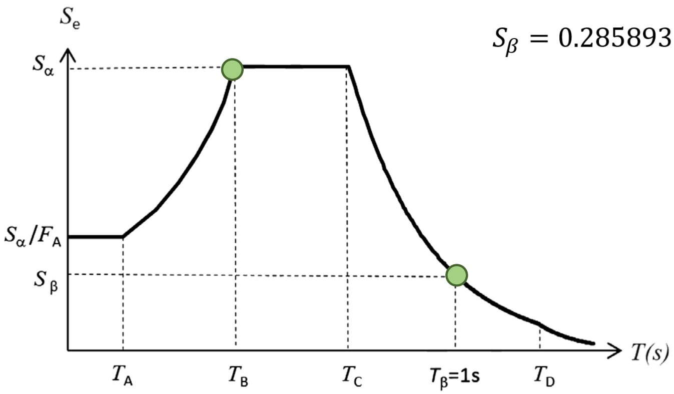
$$S_{\alpha} = 1.44265$$



Case Study Parameters

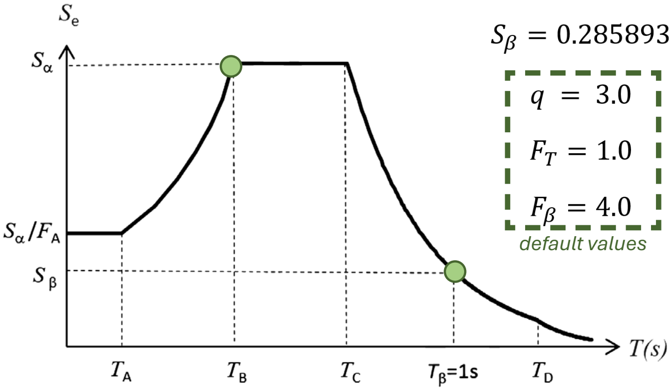
$$S_\alpha = 1.44265$$

$$S_\beta = 0.285893$$



Case Study Parameters

Europe Region



$S_\alpha = 1.44265$

$S_\beta = 0.285893$

$q = 3.0$

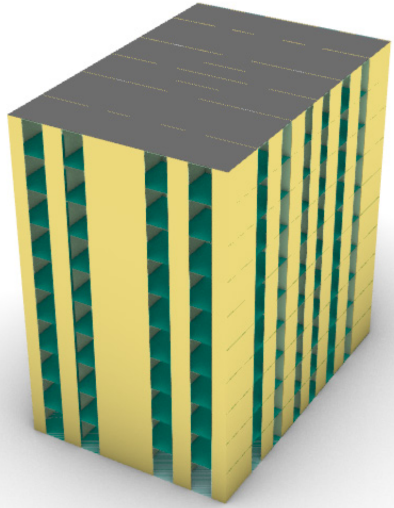
$F_T = 1.0$

$F_\beta = 4.0$

default values

Original Structure

Structure Parameters

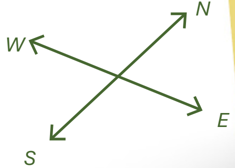


Original Structure

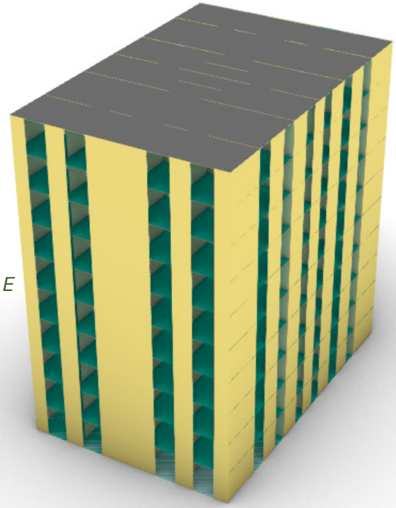
Structure Parameters

- Building period

$T_{EW} = 0.0673\ sec$



$T_{NS} = 0.0829\ sec$



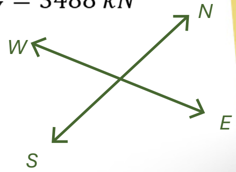
Original Structure

Structure Parameters

- Building period
- Base Shear

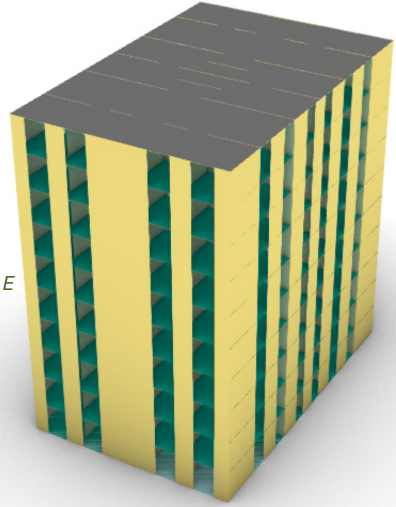
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3488\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Original Structure

Structure Parameters

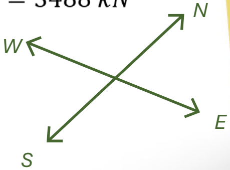
- Building period
- Base Shear

Rocking and Yielding Walls

6.7% rocking
7.6% yielding

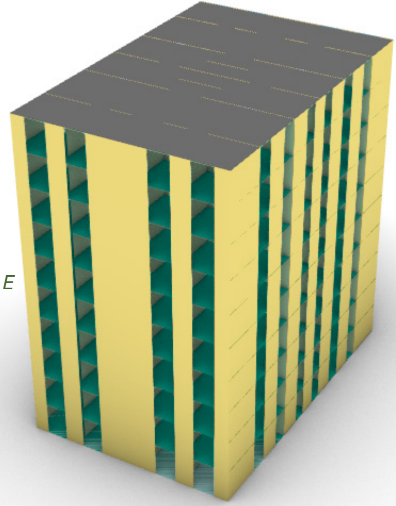
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3488\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



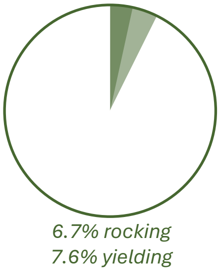
Original Structure

Structure Parameters

- Building period
- Base Shear

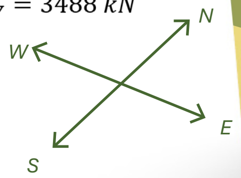
Rocking and Yielding Walls

- Only on top two stories
  - Not enough weight to resist overturning moment



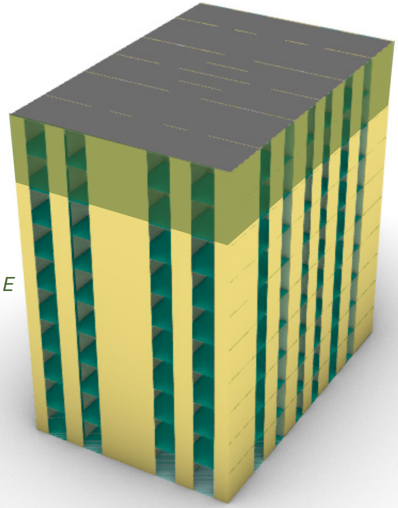
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3488\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Original Structure

Structure Parameters

- Building period
- Base Shear

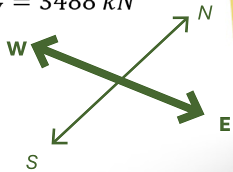
Rocking and Yielding Walls

- Only on top two stories
    - Not enough weight to resist overturning moment
- East-west direction only

6.7% rocking
7.6% yielding

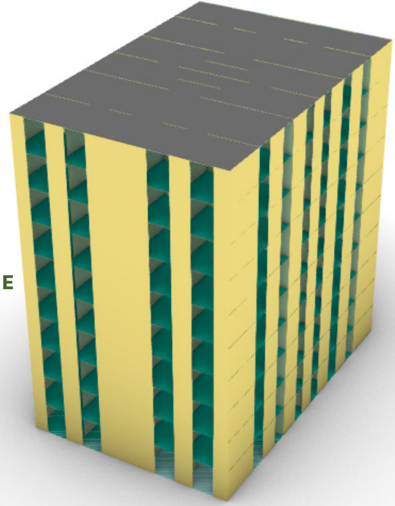
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3488\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Original Structure

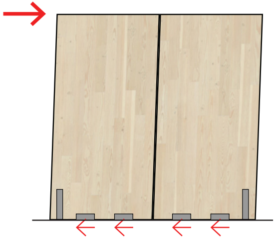
Structure Parameters

- Building period
- Base Shear

Rocking and Yielding Walls

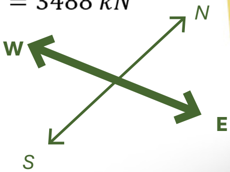
- Only on top two stories
  - Not enough weight to resist overturning moment
- East-west direction only
- Yielding in from shear, not overturning moment

6.7% rocking
7.6% yielding



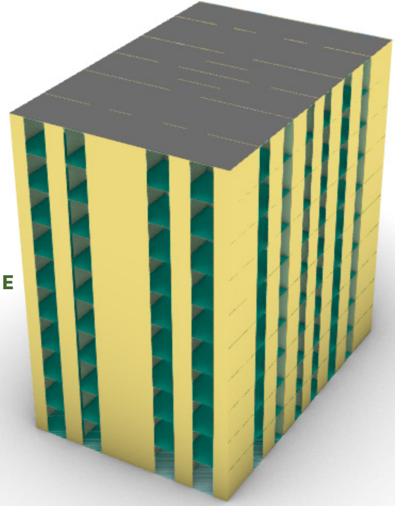
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3488\ kN$$



$$T_{NS} = 0.0829\ sec$$

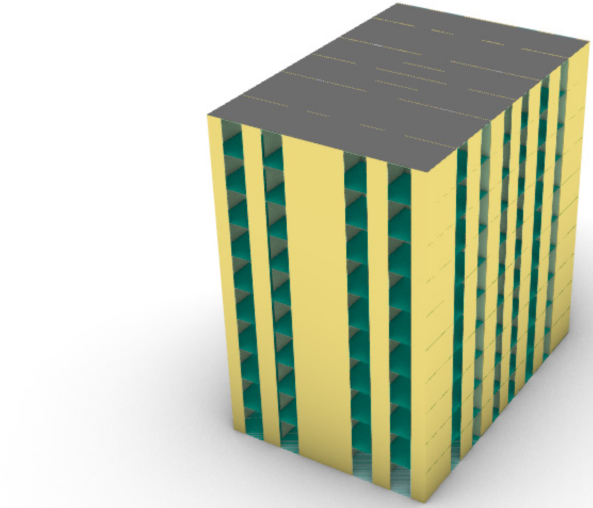
$$V_{NS} = 3513\ kN$$



Post Earthquake

Change

- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%



Post Earthquake

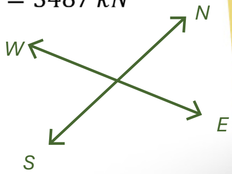
Change

- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%

Structure Parameters

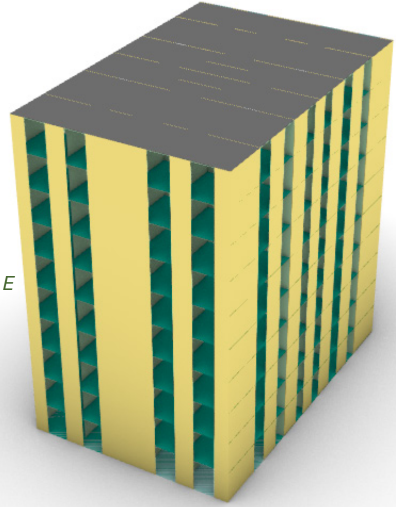
$$T_{EW} = 0.0667\ sec$$

$$V_{EW} = 3487\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Post Earthquake

Change

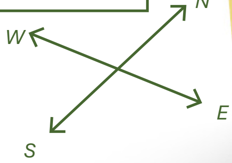
- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%

Structure Parameters

- Slight decrease in EW

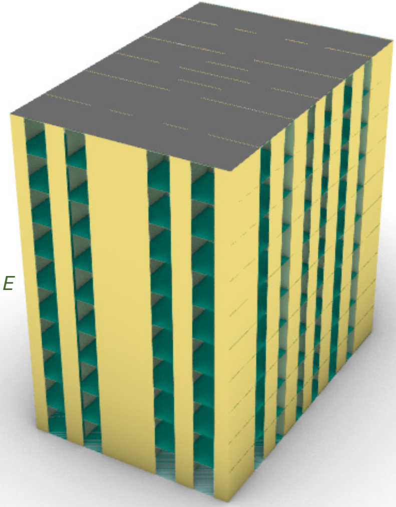
$$T_{EW} = 0.0667\ sec$$

$$V_{EW} = 3487\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Post Earthquake

Change

- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%

Structure Parameters

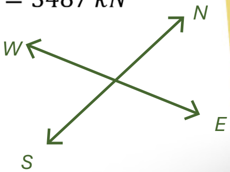
- Slight decrease in EW

Rocking and Yielding Walls

10.0% rocking
4.3% yielding

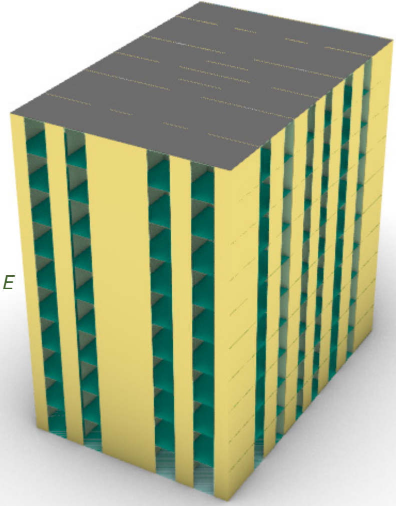
$T_{EW} = 0.0667\ sec$

$V_{EW} = 3487\ kN$



$T_{NS} = 0.0829\ sec$

$V_{NS} = 3513\ kN$



Post Earthquake

Change

- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%

Structure Parameters

- Slight decrease in EW

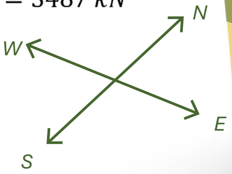
Rocking and Yielding Walls

- Only on top two stories

10.0% rocking
4.3% yielding

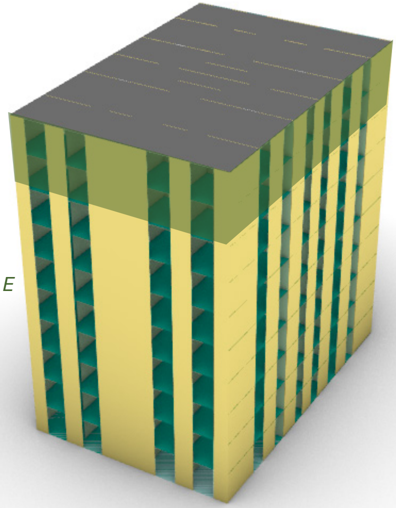
$$T_{EW} = 0.0667\ sec$$

$$V_{EW} = 3487\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Post Earthquake

Change

- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%

Structure Parameters

- Slight decrease in EW

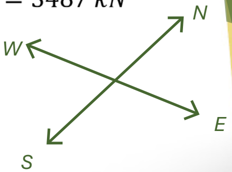
Rocking and Yielding Walls

- Only on top two stories
  - More in 9th story now

10.0% rocking
4.3% yielding

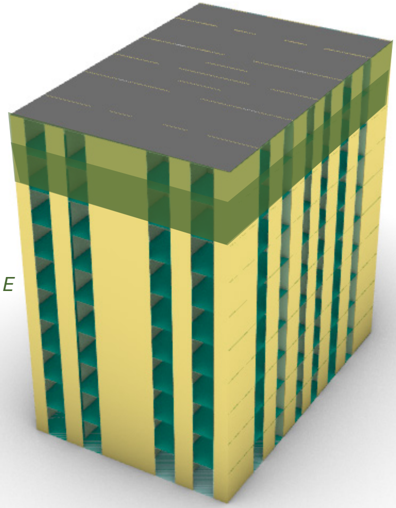
$$T_{EW} = 0.0667\ sec$$

$$V_{EW} = 3487\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Post Earthquake

Change

- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%

Structure Parameters

- Slight decrease in EW

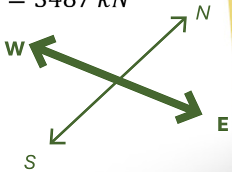
Rocking and Yielding Walls

- Only on top two stories
  - More in 9th story now
- East-west direction only

10.0% rocking
4.3% yielding

$T_{EW} = 0.0667\ sec$

$V_{EW} = 3487\ kN$



$T_{NS} = 0.0829\ sec$

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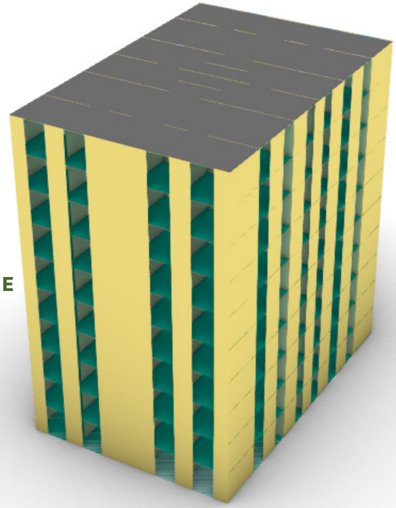


Post Earthquake

Change

- Stiffness reduction
  - Rocking walls: 80%
  - Yielded walls: 50%

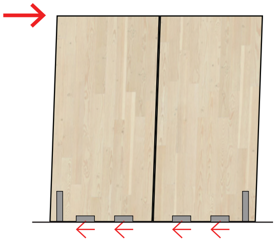
Structure Parameters

- Slight decrease in EW

Rocking and Yielding Walls

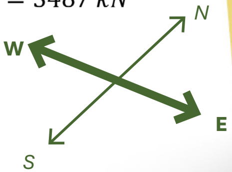
- Only on top two stories
  - More in 9th story now
- East-west direction only
- Yielding in from shear, not overturning moment

10.0% rocking
4.3% yielding



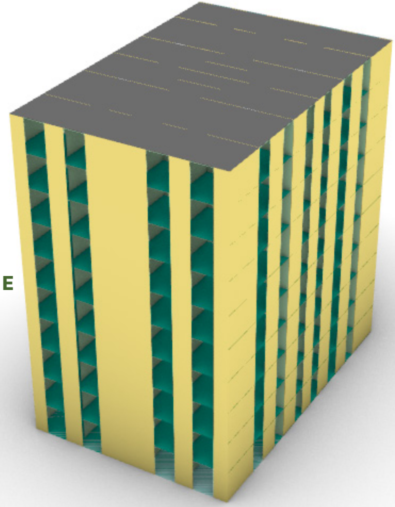
$$T_{EW} = 0.0667\ sec$$

$$V_{EW} = 3487\ kN$$



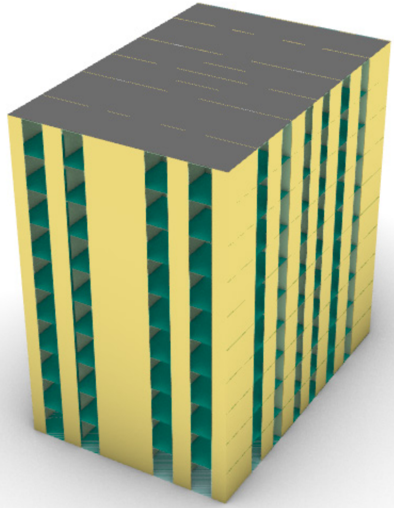
$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3513\ kN$$



Renovation

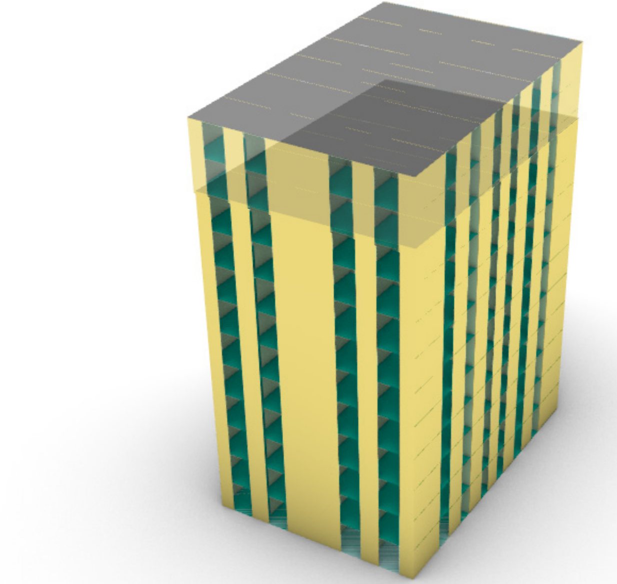
Change



Renovation

Change

- Add two new stories

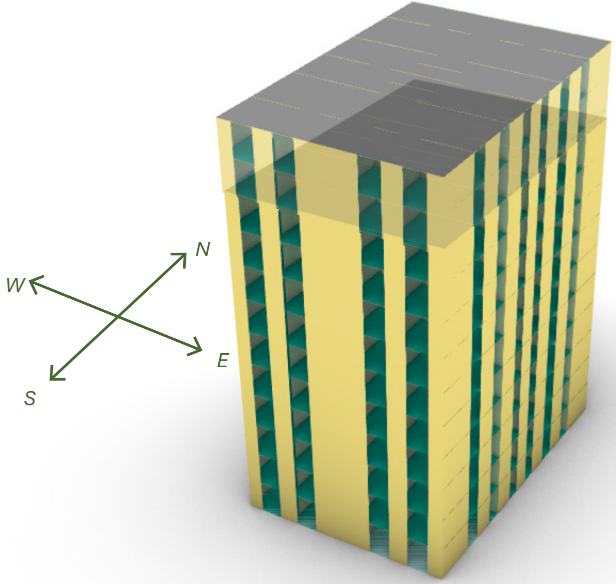


Renovation

Change

- Add two new stories

Structure Parameters



Renovation

Change

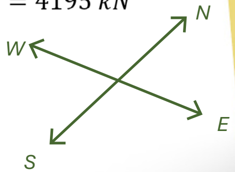
- Add two new stories

Structure Parameters

- Building period is similar
- Base shear increases

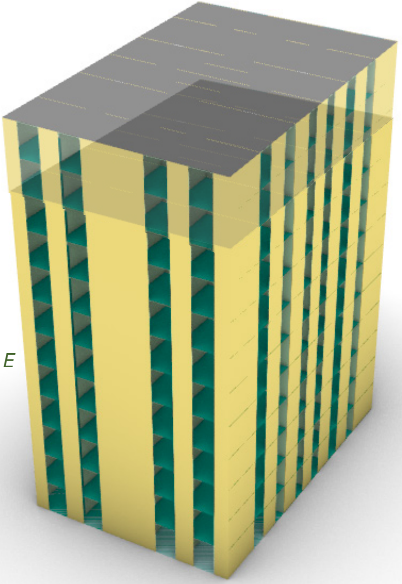
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 4195\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 4225\ kN$$



Renovation

Change

- Add two new stories

Structure Parameters

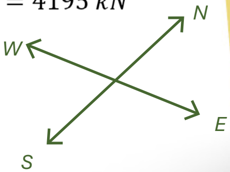
- Building period is similar
- Base shear increases

Rocking and Yielding Walls

8.3% rocking
3.6% yielding

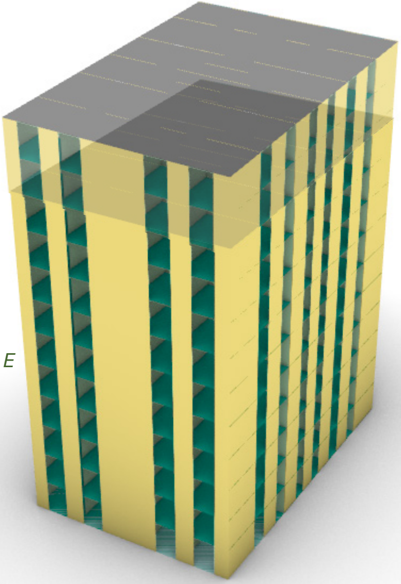
$T_{EW} = 0.0673\ sec$

$V_{EW} = 4195\ kN$



$T_{NS} = 0.0829\ sec$

$V_{NS} = 4225\ kN$



Renovation

Change

- Add two new stories

Structure Parameters

- Building period is similar
- Base shear increases

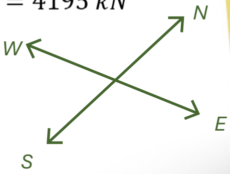
Rocking and Yielding Walls

- Only in top two stories

8.3% rocking
3.6% yielding

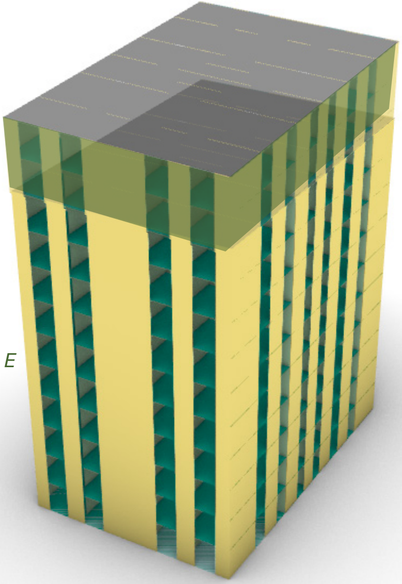
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 4195\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 4225\ kN$$



Renovation

Change

- Add two new stories

Structure Parameters

- Building period is similar
- Base shear increases

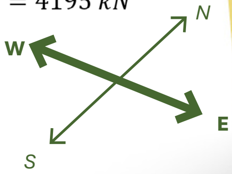
Rocking and Yielding Walls

- Only in top two stories
- East-west direction only

8.3% rocking
3.6% yielding

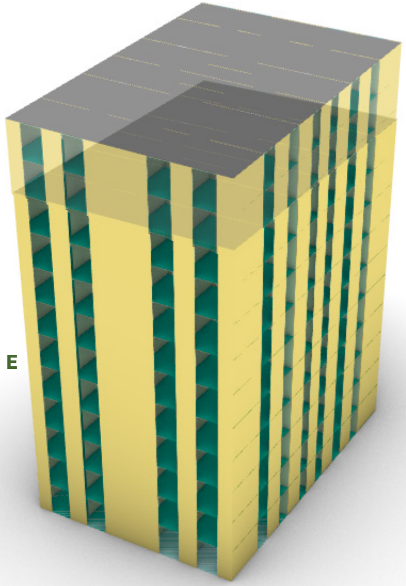
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 4195\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 4225\ kN$$



Renovation

Change

- Add two new stories

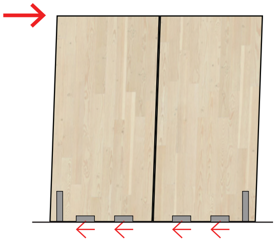
Structure Parameters

- Building period is similar
- Base shear increases

Rocking and Yielding Walls

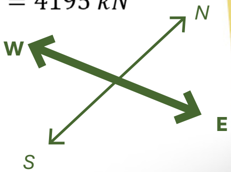
- Only in top two stories
- East-west direction only
- Yielding in from shear in angle brackets

8.3% rocking
3.6% yielding



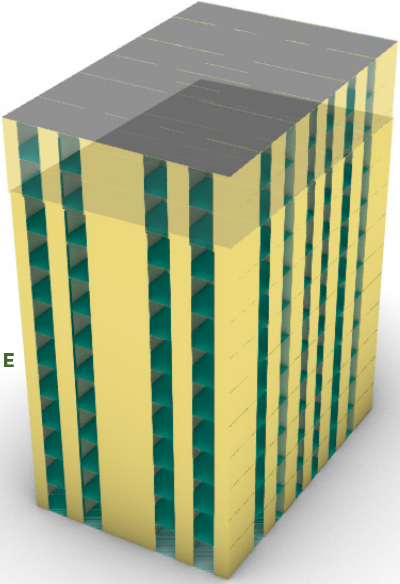
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 4195\ kN$$



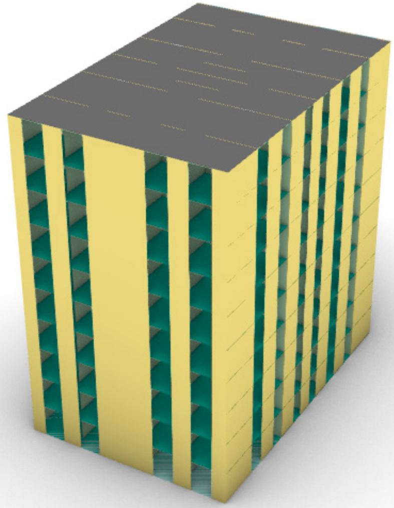
$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 4225\ kN$$



Biological Degradation

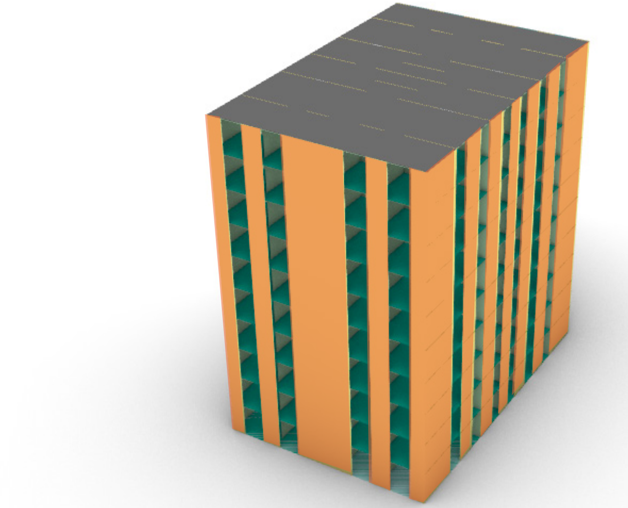
Change



Biological Degradation

Change

- 52 weeks of deterioration at exterior walls

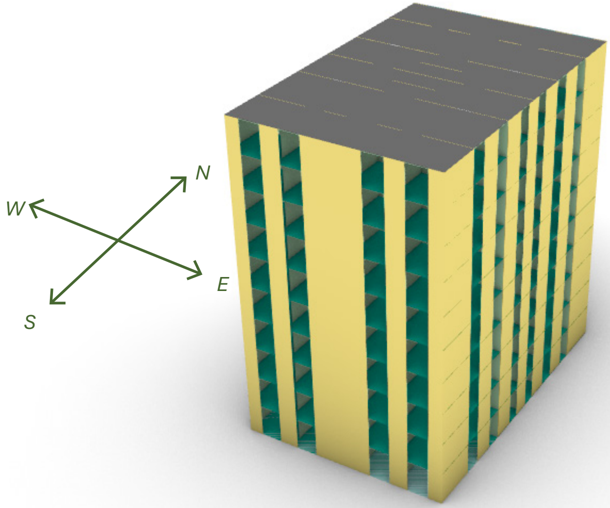


Biological Degradation

Change

- 52 weeks of deterioration at exterior walls

Structure Parameters



Biological Degradation

Change

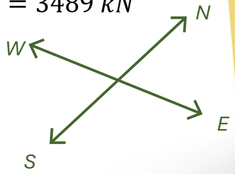
- 52 weeks of deterioration at exterior walls

Structure Parameters

- Building period and base shear remain the same

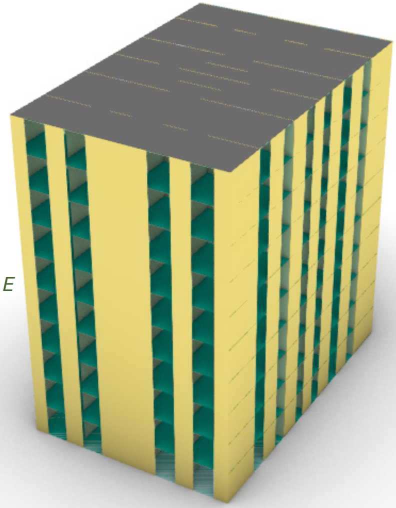
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3489\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3514\ kN$$



Biological Degradation

Change

- 52 weeks of deterioration at exterior walls

Structure Parameters

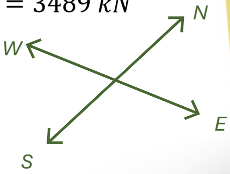
- Building period and base shear remain the same

Rocking and Yielding Walls

8.3% rocking
10% yielding

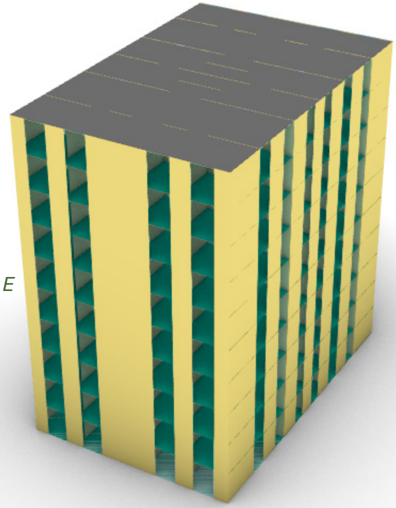
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3489\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3514\ kN$$



Biological Degradation

Change

- 52 weeks of deterioration at exterior walls

Structure Parameters

- Building period and base shear remain the same

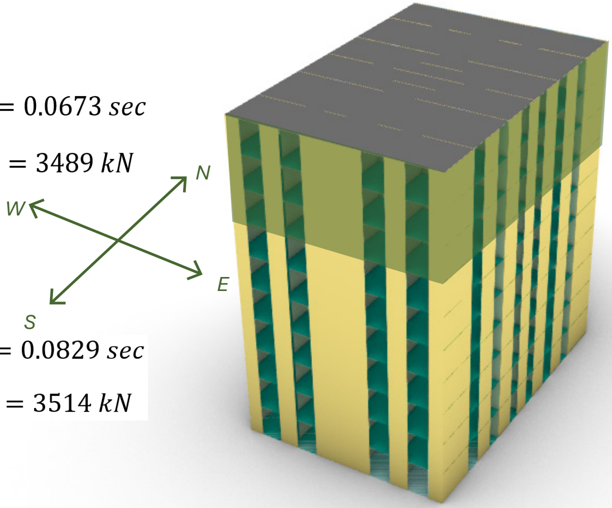
Rocking and Yielding Walls

- Stories 8-10

8.3% rocking
3.6% yielding

$T_{EW} = 0.0673\ sec$

$V_{EW} = 3489\ kN$



$T_{NS} = 0.0829\ sec$

$V_{NS} = 3514\ kN$

Biological Degradation

Change

- 52 weeks of deterioration at exterior walls

Structure Parameters

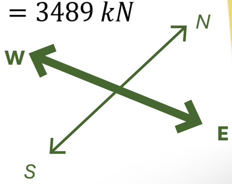
- Building period and base shear remain the same

Rocking and Yielding Walls

- Stories 8-10
- East-west direction only

$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3489\ kN$$



$$T_{NS} = 0.0829\ sec$$

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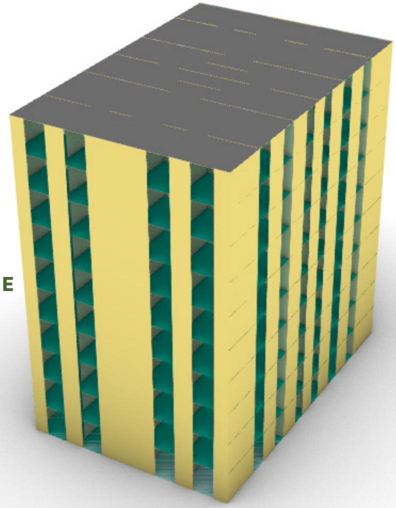


Biological Degradation

Change

- 52 weeks of deterioration at exterior walls

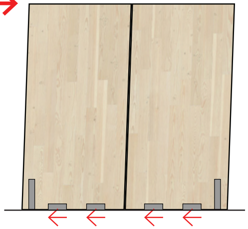
Structure Parameters

- Building period and base shear remain the same

Rocking and Yielding Walls

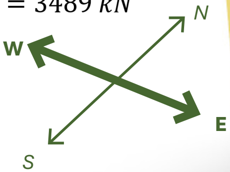
- Stories 8-10
- East-west direction only
- Yielding from shear in angle brackets, and

8.3% rocking
3.6% yielding



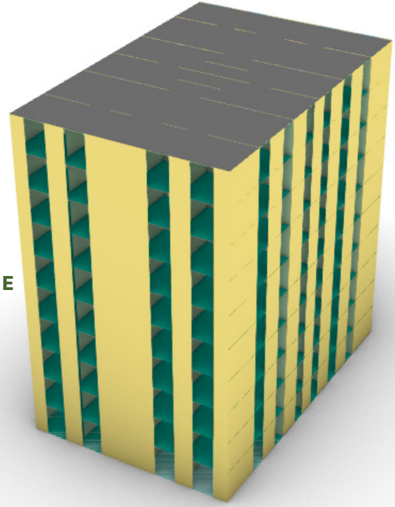
$$T_{EW} = 0.0673\ sec$$

$$V_{EW} = 3489\ kN$$



$$T_{NS} = 0.0829\ sec$$

$$V_{NS} = 3514\ kN$$



Biological Degradation

Change

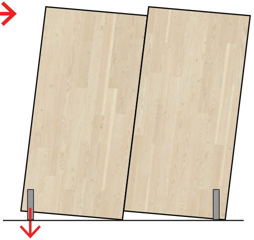
- 52 weeks of deterioration at exterior walls

Structure Parameters

- Building period and base shear remain the same

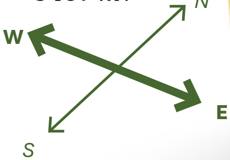
Rocking and Yielding Walls

- Stories 8-10
- East-west direction only
- Yielding from shear in angle brackets, and from overturning in hold-downs



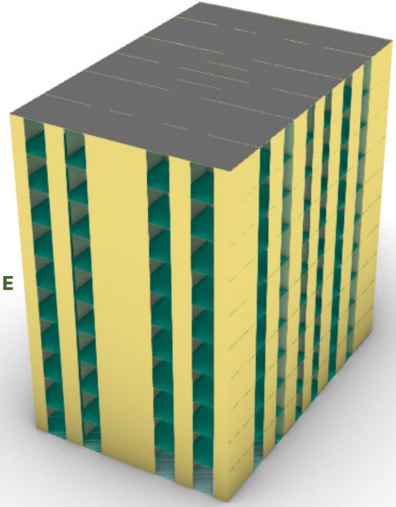
$T_{EW} = 0.0673\ sec$

$V_{EW} = 3489\ kN$

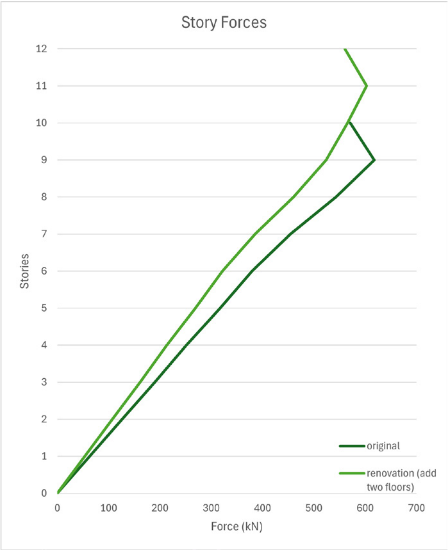


$T_{NS} = 0.0829\ sec$

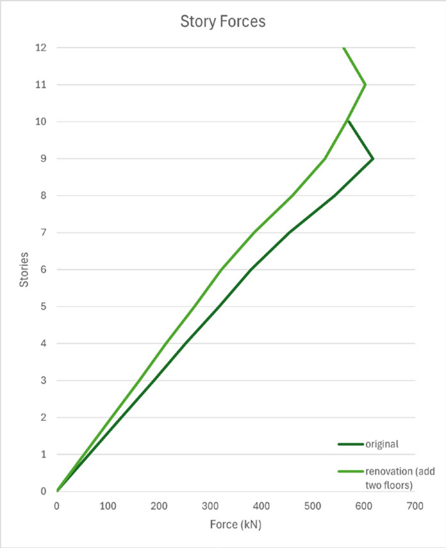
$V_{NS} = 3514\ kN$

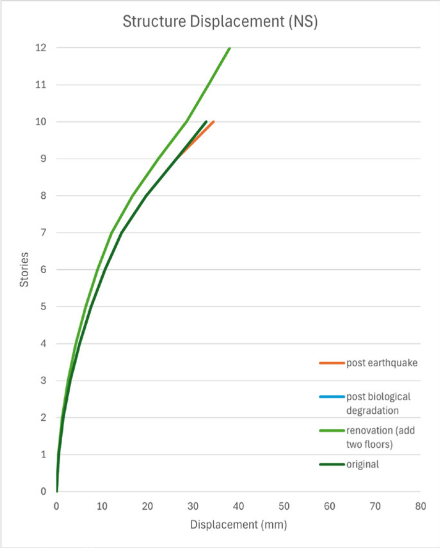


Results Comparisons

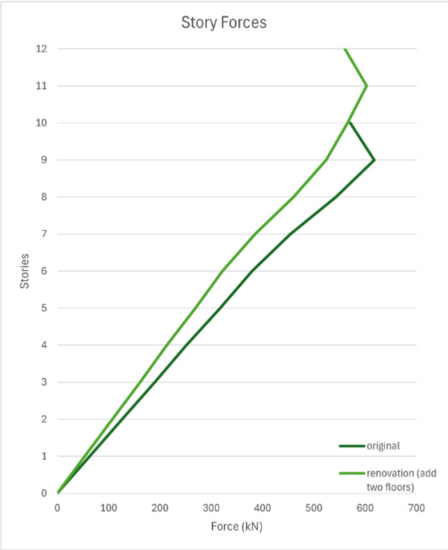


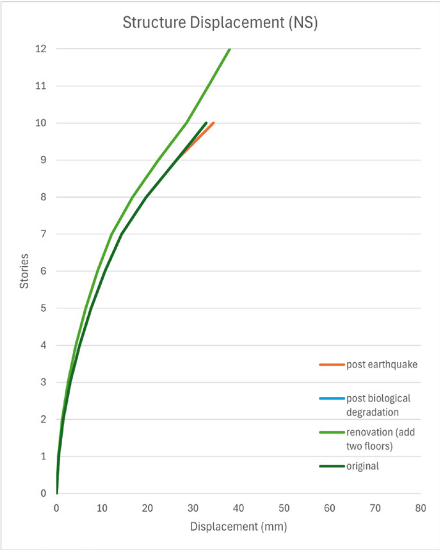
Results Comparisons

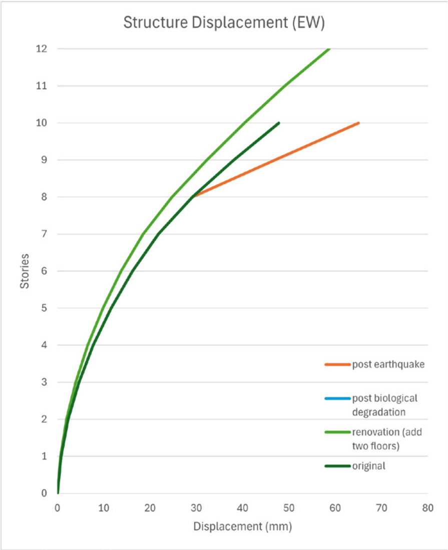




Results Comparisons





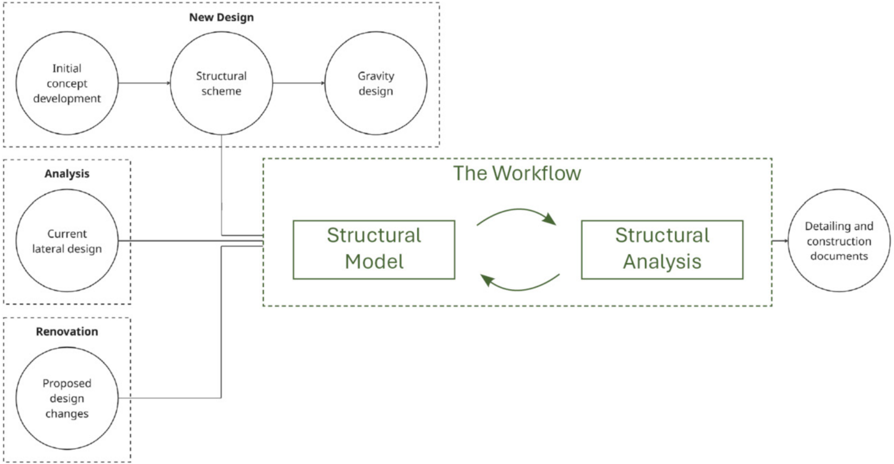


Conclusions

Conclusions

Goals

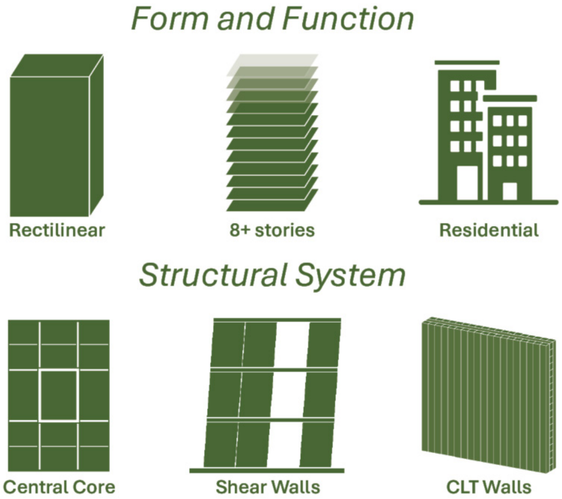
- Integrated into the main workflow



Conclusions

Goals

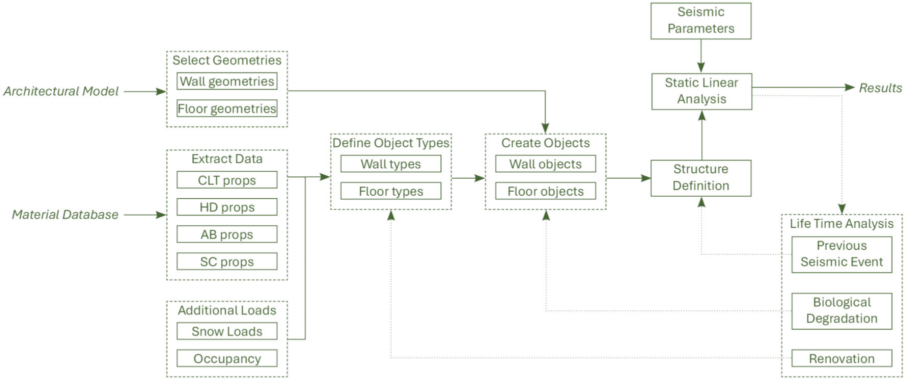
- Integrated into the main workflow
- Applicable for common tall timber construction



Conclusions

Goals

- Integrated into the main workflow
- Applicable for common tall timber construction
- Simple to implement and adapatable



Conclusions

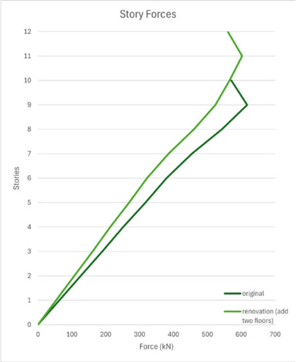
Goals

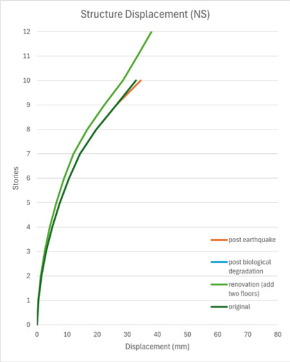
- Integrated into the main workflow
- Applicable for common tall timber construction
- Simple to implement and adapatable
- Includes lifetime analysis

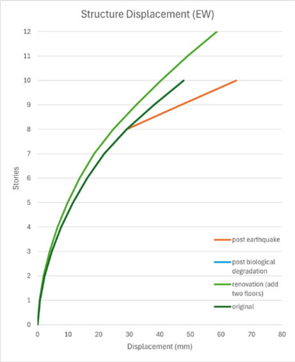
Conclusions

Goals

- Integrated into the main workflow
- Applicable for common tall timber construction
- Simple to implement and adapatable
- Includes lifetime analysis
- Output format is good for post-processing

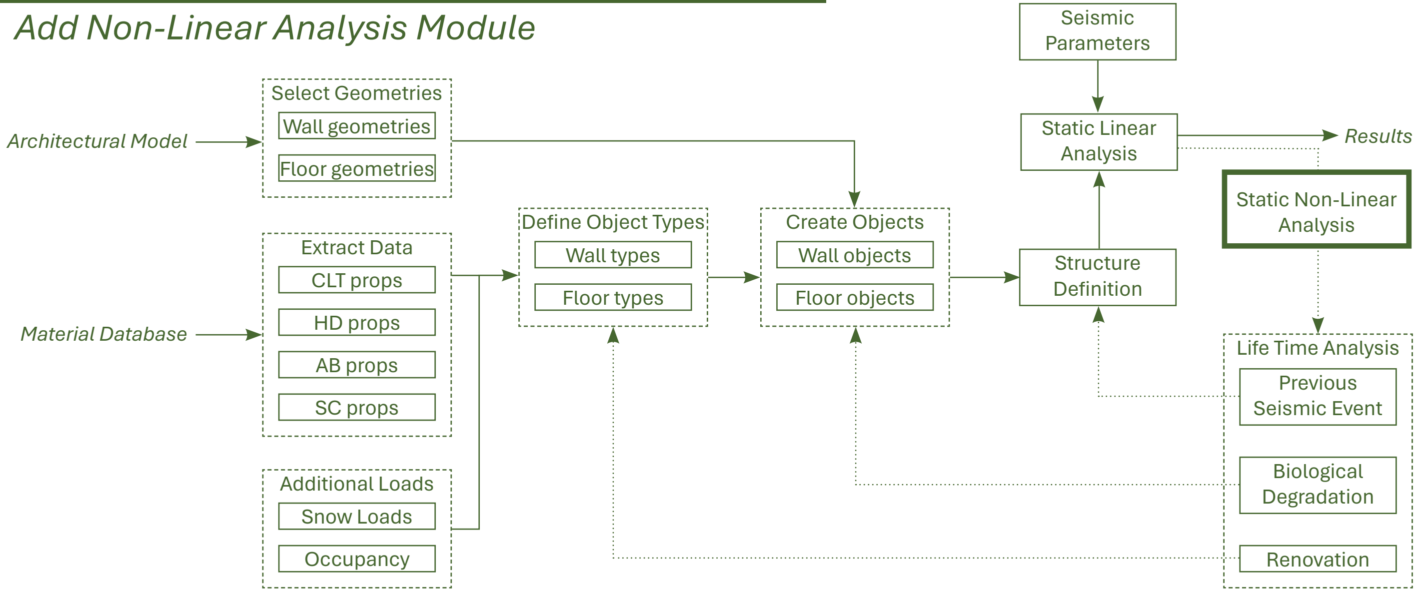






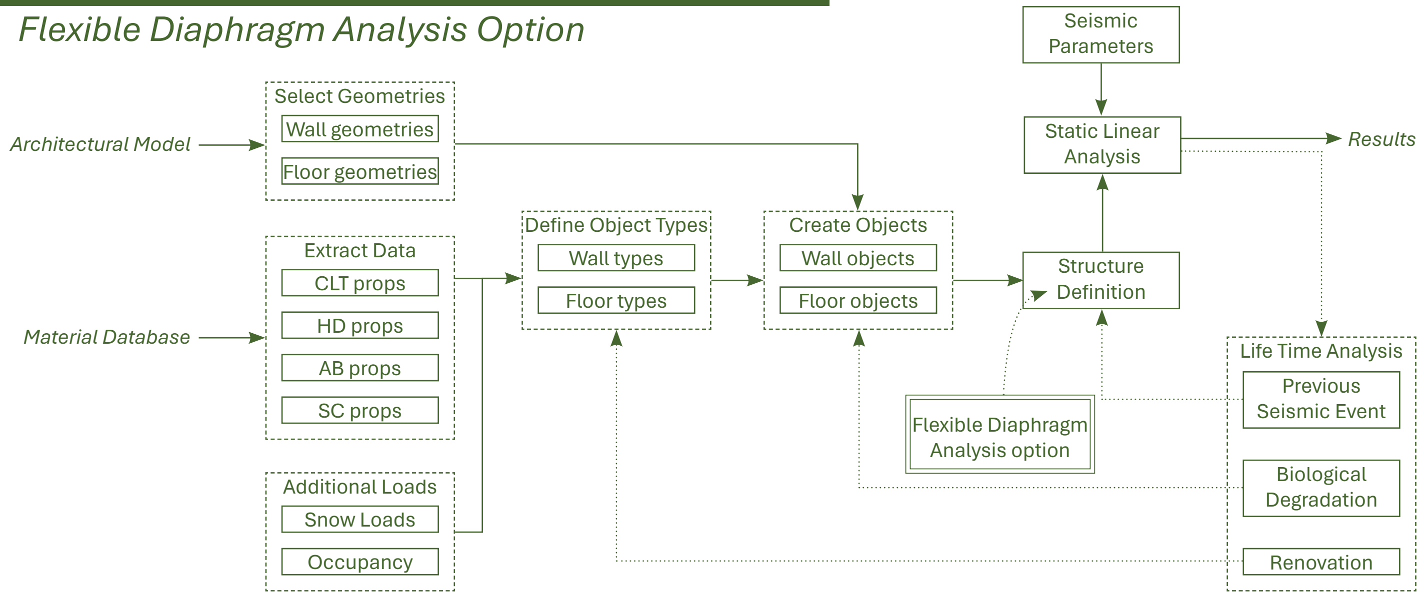
Future Development

Add Non-Linear Analysis Module



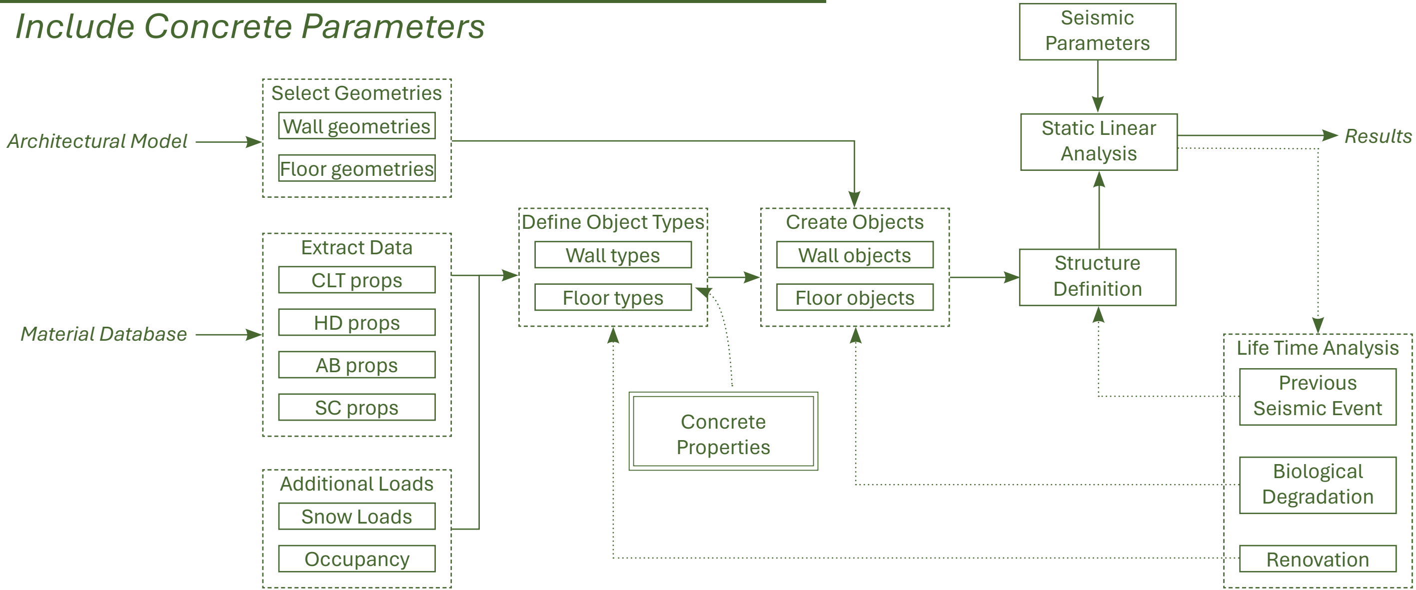
Future Development

Flexible Diaphragm Analysis Option



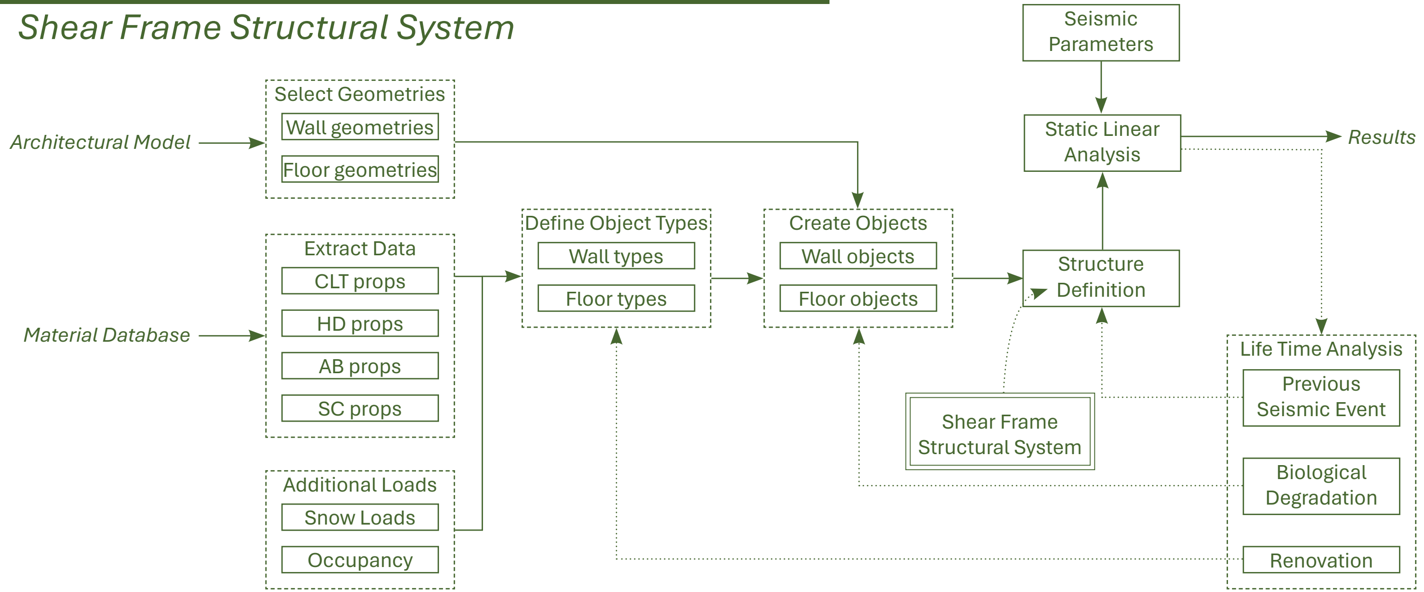
Future Development

Include Concrete Parameters



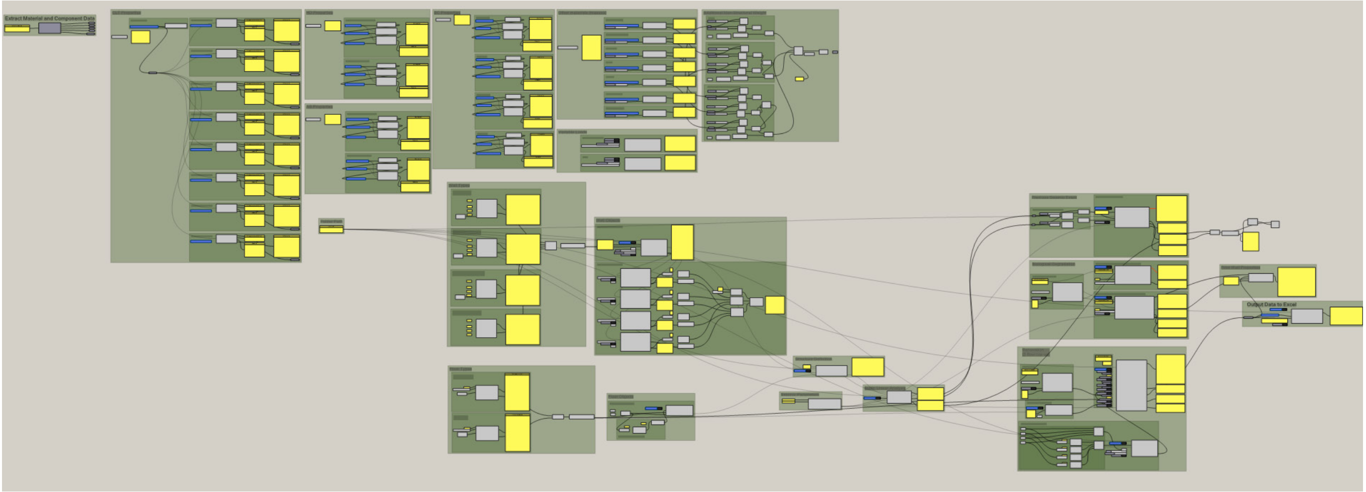
Future Development

Shear Frame Structural System



Future Development

User Interface



Thank you!

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